Trial of the Framework for the Assessment of River and Wetland Health (FARWH) in the Wet/Dry Tropics for the Daly and Fitzroy Rivers.

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TRaCK brings together leading tropical river researchers and managers from Charles Darwin University, Griffith University, the University of Western Australia, CSIRO, James Cook University, the Australian National University, Geoscience Australia, the Environmental Research Institute of the Supervising Scientist, the Australian Institute of Marine Science, the North Australia Indigenous Land and Sea Management Alliance, and the Governments of Queensland, the Northern Territory and Western Australia.

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Front cover - *The Douglas River, a tributary of the Daly River, during the dry season.* Photo by Ian Dixon

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Fitzroy (Mardoowarra) River

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Permits

This research was conducted in accordance with the following permits: Northern Territory Parks and Wildlife (No. 33609); Northern Territory Fisheries (No. 2009-2010/S17/2762); Charles Darwin University Animal Ethics (No. A09013); Western Australia Department of Environment and Conservation (No. SF006973); Western Australian Department of Fisheries Exemptions (No. 191-2009-27); and University of Western Australia Animal Ethics (No. AEC RA/3/100/884).

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1 Executive summary

Australian states and territories are signatories to the National Water Initiative (NWI), the progress of which is assessed by the National Water Commission (NWC). An important NWI outcome is the delivery of a nationally compatible market, with a regulatory and planning-based protocol for managing surface and groundwater resources for rural, social and environmental outcomes. A key component of this goal was to develop a nationally consistent approach to river health assessment and reporting. During 2006, the *Australian water resources 2005 discovery phase* (AWR 2005) found that, typically, information and knowledge on river health were patchy and the capacity for developing a national approach to river health assessment was limited. Consequently, a national framework for river heath assessment—The Framework for the Assessment of River and Wetland Health (FARWH)—was developed.

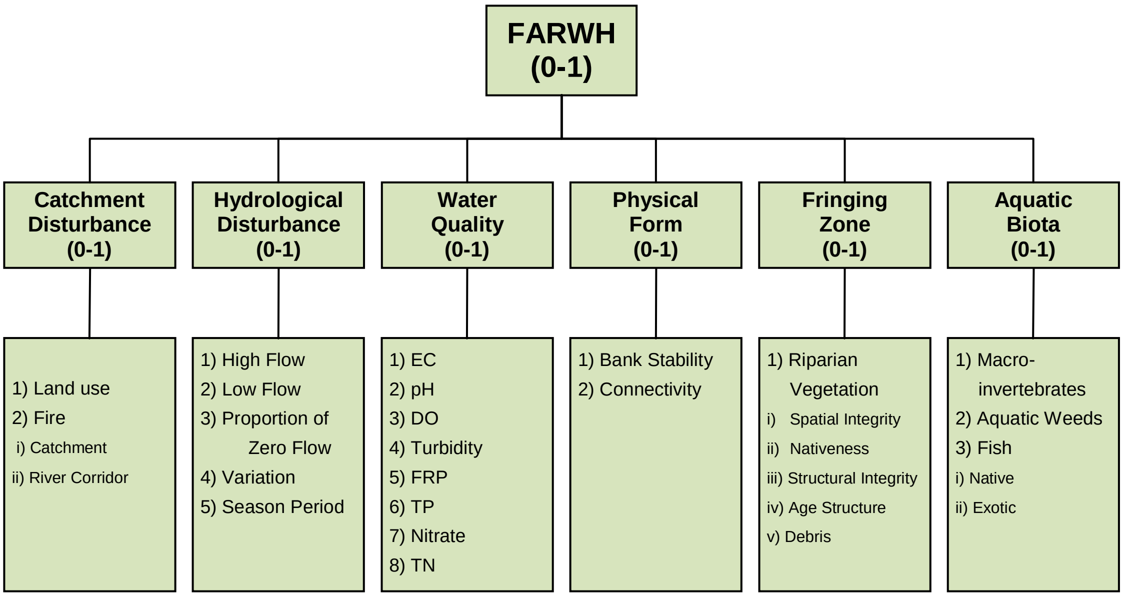
Over the past few years, the FARWH framework has been trialled and tested in focal catchments across Australia. The wet/dry tropics of Australia were chosen as one of the key areas to trial the framework. Tropical rivers of northern Australia are internationally recognised for their high ecological and cultural values. Not only does the climate of the wet/dry tropics fundamentally differ from temperate Australia, but the nature of environmental impacts on the aquatic environment also differs. Unlike many other tropical systems, and their temperate Australian counterparts, they have largely unmodified flow regimes and are comparatively free from the impacts typically associated with intensive land use (see Douglas et al. 2005). The region has experienced very little intensive development; cattle grazing of native pastures is the dominant land use. Other major threats to northern Australian rivers include altered fire regimes, and weed and feral animal invasions. These unique catchment conditions and the vastness of the region pose scientific and practical challenges for assessing river heath.

Assessment of the FARWH in the wet/dry tropics comprised two distinct phases: an initial desktop assessment in the Darwin Harbour and Ord River catchments using existing data, followed by a field-based assessment in the Daly and Fitzroy River catchments. Traditional owners recognise the Fitzroy River by the name Mardoowarra River. The project was managed by the Tropical Rivers and Coastal Knowledge research hub (TRaCK), which includes the University of Western Australia, as lead for Western Australia (WA), Charles Darwin University, for the Northern Territory (NT) and Griffith University, for Queensland (Qld), in association with:

- The NT Department of Natural Resources, Environment, the Arts and Sport
- WA Department of Water
- Qld Department of Environment and Resource Management
- eWater CRC.

In brief, the FARWH has established a general approach for assessing river health, based on reference conditions, to be reported at the surface water management area(SWMA) as defined by the NWC (2007). The framework includes the following six themes of river and wetland health: catchment disturbance, hydrological disturbance, fringing zone, physical form, aquatic biota and water quality (Figure 1.1). The objectives of the FARWH trials were to establish suitable metrics under each theme that were sensitive to pressures associated with major land-use changes, and appropriate for the rapid assessment and reporting of river health.

Figure 1.1: Flow diagram of the six FARWH themes and their subindices.



This document describes in detail the field trial of the FARWH in the Daly and Fitzroy river catchments. The field trials were undertaken over the 2009 dry season (July–October). Forty-one and 37 sites were assessed in the Daly and Fitzroy rivers respectively. Data was collected at each site for the water quality, physical form, fringing zone and aquatic biota themes. The hydrology and catchment disturbance themes were based on existing data. The desktop trials have been previously reported by Dixon et al. (2009), although key results from this study have been included here to compare results.

The approaches and key findings from the field trials, with comparison of results from the desktop trials (where appropriate), are provide in the following sections.

Surface water management area

SWMA boundaries were first created by Geoscience Australia in 2000 and used in the National Land and Water Resources Audit (NLWRA; Norris et al. 2001). These boundaries were refined for the desktop trials in the Daly River catchment (Dixon et al. 2009) to reflect current interests of government land and water managers. An important component of tropical FARWH, clearly stated by state and territory government stakeholders, was the need to calculate subcatchment FARWH scores. The current level of development across northern Australia is typically represented by a disturbed subcatchment surrounded by a large area of relatively undisturbed catchment. Based on this, the following modifications were used in the field trials reported here:

- In the Daly River catchment, the SWMA boundary was stratified into ‘developed’ and ‘undeveloped’ SWMAs to align with the priorities of the NT Government. The proportion of total catchment area of the developed and undeveloped zones was 19% and 81% respectively.
- In the Fitzroy River catchment, primary disturbances (i.e. cattle grazing and altered fire regimes) are widespread throughout the catchment, and therefore it was not necessary to modify the existing SWMA to reflect management interests.

Reach and site selection

The identification of reaches within the SWMA formed the basis on which data on river health metrics was collected and assessed (NWC 2007). Guidelines to identify reaches and survey sites were established by the NWC (2007). The NLWRA reach network provided a potentially suitable method for identifying reaches. These reaches have a minimum length of 5 km, a minimum catchment size of 50 km^2 and break where stream power doubles (based on gradient and catchment size). While the NLWRA reaches were applied successfully to the Ord River trial, they were inadequate for identifying reaches in the Darwin Harbour catchment, due to the low relief. Instead, stream order was used for this study.

Reaches used in the Daly River catchment were those defined by the NLWRA, which under-represented low-order streams. There were 386 reaches (4744 km of stream length) within the Daly River catchment. Site selection was limited to perennially flowing rivers and the availability of resources to access sites in a remote region. Sites were therefore selected on criteria that did not provide for the requirement of randomly chosen sites. (NWC 2007). Priority was given to sites with a gradient of catchment pressures. These sites were examined for responsiveness of indicators to cattle, pigs and buffalo disturbance. Of the overall FARWH stream network, 1587 km (149 reaches; 39% of total length) were classed as perennially flowing. Of the perennial stream network length, 43% were located within the developed zone and 57% were located within the undeveloped zone of the Daly River SWMA.

An automated reach network was developed for the Fitzroy catchment as NLWRA audit reaches were not available. The automated approach identified a reach network of 11 900 km, with 50% first-order streams and stream orders up to six represented. Due to the lower resolution of the automated stream network, the lower Fitzroy River is considered a sixth-order stream. The remoteness of sites, rough terrain, as well as requirements for community engagement, resulted in the largely opportunistic selection of sampling sites, rather than the required randomised approach. Thirty-seven sites were selected to represent the variety of land-use intensities, where possible, although sites sampled were largely determined by accessibility.

Identification of reference condition

The identification of reference conditions in the desktop trials have been previously described in detail by (Dixon et al. 2009). In general, the definition of reference conditions was constrained by limited knowledge of the natural, temporal and spatial variability of conditions/biota across northern Australian catchments. Reference conditions for the field-based assessments were therefore defined using a variety of techniques, as outlined below.

- In the Daly catchment the methodology for defining reference sites or condition varied for each of the FARWH themes.
- In the Fitzroy catchment, reference conditions were identified within three broad geographic boundaries (mid and upper catchment and small tributaries), which were defined following a review of the variation in biophysical conditions across the catchment. Reference conditions for the fringing zone and physical form themes were based on minimally disturbed sites (s*ensu* Norris et al. 2001). Within each subregion, sites with the highest riparian condition and lowest pressure were chosen to provide an appropriate reference. Reference condition for the fish subindex was based on expected species presence. This was derived from a review of recent fish-survey data and expert opinion.
- The development of a water quality index for the Daly and Fitzroy river catchments was constrained by lack of knowledge about the ecological implications of water quality deviations from reference conditions. Reference conditions for water quality parameters were established following a review of current literature and the use of expert knowledge of the potential ecological significance of changes in water quality parameters. The aim of this assessment was to develop a water quality index that was transparent and simple to understand, and that reflected the ecological significance of changes in water quality over time. Based on these criteria, reference conditions for a variety of water quality attributes were based on the natural range or 'reference' conditions. Percentile values were calculated, as recommended by the National Water Quality Management Strategy (WQMS), to provide information about the reference condition.

- The majority of rivers and reaches in the Daly and Fitzroy river catchments have low hydrologic disturbance and do not have modelled flows. Consequently, a qualitative assessment of land-use impacts on hydrologic disturbance was required. A variety of land-use classes was identified and qualitative weightings, indicative of their hydrological effects, were derived following a review of literature and the use of expert opinion.

Catchment disturbance theme

The objectives of this chapter were to describe a new method of calculating two subindices: a fire subindex, and to apply new weightings to land-use classes. The fire index was first trialled in the desktop assessments in the Darwin Harbour and Ord River catchments. The index worked well and was easy to calculate (Dixon et al. 2009) and was therefore retained for the field trials in the Daly and Fitzroy river catchments. The fire subindex comprised two subindices: i) burnt catchment and ii) burnt river corridor. A revised weighting system for impacts of land uses as defined by the *Australian land use and management classification version 6* (BRS 2007) was successfully applied in the desktop trials and retained for the field-trial assessment of FARWH. This theme does not address point sources of pollution, such as wastewater discharges from mines and wastewater plants, though two were present in the Daly catchment but, based on regulatory monitoring, have negligible river health impact.. Specific outcomes from the field trials are provided below:

- Using a revised weighting system for impacts of land uses, the land-use subindex was effectively applied to both catchments. The weightings used were modified, based on extensive literature reviews by the WA Department of Water (Storer et al. 2010).
- Different methods for calculating the fire index score have been applied in the two study catchments. The method developed in the desktop trial was applied to the Fitzroy SWMA for consistency. An alternative method to produce the fire subindex was developed for the Daly River catchment to incorporate fire frequency over a five-year period.
- The method applied to the Daly SWMA is more complex and likely to provide a more sensitive approach for assessing the impact of fire on river health.

Integration of land use and fire into the catchment disturbance theme for the SWMA (Fitzroy River) or stratified zone (Daly River) used a land use and fire weighting of 80% and 20% respectively. Results for the CDI are provided in Table 1.1.

Table 1.1: FARWH scores for land use, fire and the final catchment disturbance score calculated for the Daly and Fitzroy river catchments.

Component	Daly River		Fitzroy River
	Developed	Undeveloped	
Land use	0.71	0.82	0.67
Burnt catchment	0.82	0.80	0.83
Burnt river corridor	0.79	0.80	0.87
Catchment disturbance	**0.73**	**0.82**	**0.71**

Hydrological disturbance theme

The objectives of this chapter were to 1) provide a quantitative assessment of the impact of current and future surface and groundwater extraction on stream flows, and 2) provide a qualitative assessment of changes in stream flow. A modified flow stressed ranking (FSR) procedure was applied for both the desktop and field trials to assess the impact of land-use change on river flows. The FSR procedure provides an objective ranking of threats to river health based on the level of water extractions and consumptive use (SKM 2005). The procedure compares the following five flow indices between unimpacted conditions (pre-disturbance) and current (disturbed) hydrologic conditions: magnitude of high flows, magnitude of low flows, proportion of zero-flow days, seasonality and variability of flow (SKM 2005). The FARWH trial is the first time the procedure has been trialled in the wet/dry tropics.

The majority of rivers and reaches in the Daly and Fitzroy river catchments have low hydrologic disturbance and do not have modelled flows. A quantitative approach (using current and modelled flow data) could be applied to only 6% of FARWH reaches in the Daly River catchment to assess the impact of surface and groundwater extraction. Consequently, a qualitative assessment of land clearing, cattle grazing, fire and water extraction on hydrologic disturbance was undertaken. This assessment was based on a literature review and expert opinion. Aggregation of the five FSR indices (high flow, low flow, proportion of zero flow, variation and seasonal period) was completed at the reach scale by calculating the arithmetic mean.

The FSR procedure produced results with reasonable confidence when applied to modelled concurrent datasets (Darwin Harbour, Ord River and parts of the Daly River catchments). The results of both quantitative and qualitative application of the FSR for the field trials are presented below (Table 1.2).

Table 1.2 FARWH scores for quantitative and qualitative assessment of hydrological disturbance in the Daly and Fitzroy River catchments.

FSR procedure	Daly River	Fitzroy River
Quantitative groundwater extraction Groundwater and surface water extraction	 0.66–0.88 0.38–0.53	No data available
Qualitative	**0.96**	**0.98**

Water quality theme

The development of a water quality index for the Daly and Fitzroy river catchments was constrained by a lack of knowledge about the ecological implications of water quality deviations from reference conditions. The aim of this assessment was to develop an index that was transparent and simple to understand, and that reflected the ecological significance of changes in water quality over time. Based on these criteria, thresholds were established for a variety of water quality attributes based on the natural range or reference conditions. Percentile values were calculated, as recommended by the WQMS, to provide information about the reference condition. This method was first applied in the desktop trials (Dixon et al. 2009) and further modified for the field trials reported here.

Ecological disturbance thresholds were devised for six water quality parameters (electrical conductivity, µS/cm; pH; turbidity, NTU; dissolved oxygen, % saturation and mg/L; nitrogen, µg/L; and phosphorus, µg/L). Scores were based on the natural range of reference sites, literature reviews and expert opinion of perceived levels of degradation. With insufficient data and knowledge surrounding the natural variation in the Fitzroy region, there were substantial limitations to adopting the preferred methodology of, first, setting reference condition and, second, setting bands based on percentiles. These levels need to be regarded with caution, as they require further development based on substantial knowledge gaps and uncertainties.

The lowest FARWH score of all measured water quality parameters and was used to calculate the final FARWH water quality score. This rule acknowledges that the implied ecological degradation of any one attribute will not be compensated by an attribute that has a value that falls within the natural range. The FARWH water quality score for the Daly River catchment undeveloped zone was **1,** and for the developed zone, **0.91**. The lower scoring for the developed zone appears to reflect the different levels of disturbance between the strata. All reaches scoring less than 1 were found to be first-order streams within the developed agricultural zone.

Final integrated scores for the Water quality theme were **0.96** and **0.78** for the Daly and Fitzroy river catchments respectively.

Physical form theme

The physical form theme consists of two subindices: 1) bank stability (bank erosion) and 2) connectivity (longitudinal connectivity of surface water). Bank stability was assessed using field measurements of soil, exposed tree roots, slumping, gullying and undercutting, following the Tropical Rapid Appraisal of Riparian Condition (TRARC) approach (Dixon et al. 2006). The conversion of TRARC scores to the FARWH physical form theme is described in detail in the desktop trial report (Dixon et al. 2009). For the field trials presented here, a modified 'inverse ranking' method was adopted to integrate the five erosion metrics.

The connectivity subindex represented an assessment of how human-built structures impeded the longitudinal connectivity of habitats for aquatic biota. Only large dams, weirs and causeways were deemed appropriate for the assessment of connectivity in both the Daly and Fitzroy river catchments. Human-built structures were assigned a weighting based on the type of physical barrier (e.g. dam, weir or causeway) and a second weighting for the duration of time that each barrier restricted the movement of aquatic biota (e.g. dry season only, or entire year). The final connectivity weighting represented the product of the two (*sensu* NWC 2007).

The bank stability and connectivity subindices were weighted for integration to a final physical form theme score for the SWMA or stratified zone: bank stability was given a higher weighting (80%) than connectivity (20%), as erosion is more likely to vary in the future than the number of large dams or weirs in the catchment.

Forty-one and 35 sites were surveyed using the TRARC methodology (Dixon et al. 2006) in the Daly and Fitzroy river catchments respectively. In the Daly River catchment, this comprised 32 reaches in the developed zone and nine in the undeveloped zone. The 35 sampling sites in the Fitzroy River catchment represented 3% of the 1191 FARWH reaches. Final bank stability scores were **0.84** and **0.77** for the developed and undeveloped zones in the Daly River catchment. The final bank stability subindex score for the Fitzroy River SWMA was **0.82**.

Nine in-stream structures were identified in the Daly River catchment and two in the Fitzroy River catchment. The final connectivity subindex scores were **0.95** and **1.00** for the developed and undeveloped zones of the Daly River catchment respectively, and **0.99** for the Fitzroy River SWMA. Integration of the subindices resulted in a final physical form score of **0.84** (**0.86** developed, **0.82** undeveloped) for the Daly River catchment and **0.85** for the Fitzroy River catchment

Our limited knowledge of natural variability of reaches in the catchment raises the issue of using generalised reference condition. Further investigation is required to incorporate natural characteristics related to stream geomorphology, soils and vegetation types. There are currently no issues related to the connectivity subindex. As it currently stands, the approach suggested by the NWC (2007) to score connectivity is suitable for the wet/dry tropics.

Fringing zone theme

The fringing zone theme is an assessment of riparian vegetation condition. For the purpose of this theme in the wet/dry tropics, the riparian zone was defined as the area extending from the water’s edge (river channel) to where there was a distinct change in vegetation and landform.

We applied on-ground assessments of riparian condition following the TRARC method. TRARC requires visual assessment of riparian condition indicators, including plant cover and regeneration, and the occurrence of weeds, erosion and other pressures (Dixon et al. 2006). TRARC was converted to five FARWH metrics (spatial integrity, nativeness, structural integrity, age structure, and debris) using methods described from the desktop trials (Dixon et al. 2009). For the field trials, an additional modification was made: ‘expert rules’ were used to recalculate grass-cover scores based on their matching canopy cover.

Forty-one sites were surveyed in the Daly River catchment using the TRARC methodology. Final scores for the developed and undeveloped zones were **0.83** and **0.77** respectively. Aggregation of these scores to the SWMA produced a final fringing zone theme score of **0.80**. Thirty-five sites (3% of the 1191 FARWH reaches) were surveyed in the Fitzroy River and the final fringing zone score of **0.86** was calculated.

The interim Department of the Environment, Water, Heritage and the Arts riparian protocol recommends the use of remotely sensed data for determining spatial integrity (i.e. riparian width and continuity). Because this resource was not used in this study we applied the 'canopy continuity' and tree-clearing indicators of TRARC. Riparian width is not scored using TRARC. Instead, the tree-clearing indicator of TRARC (see Dixon et al. 2006), which measures the extent of riparian/buffer clearing, was inverted and applied as a surrogate measure of riparian width. Furthermore, because of the limited clearing of riparian vegetation in the wet/dry tropics, assessment using remote sensing would provide information only on vegetation width and longitudinal continuity; features we know are relatively undisturbed. With management activities focused on localised disturbances caused by weeds, overgrazing, fire and feral animals (pressures more likely to affect the understorey), on-ground assessment is more appropriate when applied at manageable scales.

Tropical riparian zones are highly variable and may require separation into more complex classifications, and therefore we acknowledge that more intensive research is required to properly define reference condition for this theme. Due to our limited knowledge of the natural variability of riparian community structure and the range of natural geomorphic types (which influence community structure) caution is required when interpreting these FARWH results.

Aquatic biota theme

The aquatic biota theme consists of three subindices: 1) macroinvertebrates; 2) fish; and 3) aquatic weeds. The Aquatic Biota Index is intended to represent the response of biota to changes in environmental conditions (NWC 2007). The macroinvertebrate and fish metrics were determined, based on field samples, and scores were calculated using an observed/expected (O/E) ratio. Exotic species of fish and aquatic macrophytes were based on field observation of their presence or absence.

AUSRIVAS (Australian River Assessment System) models (genus level for the Daly River and family level for the Fitzroy River) were used to assess the macroinvertebrate subindex. The models were derived from a range of reference sites in each region. The models predict macroinvertebrate species at each of the FARWH sites, using a range of predictor variables.

The fish subindex comprises two components: 1) an O/E ratio of fish species, and 2) an exotic fish presence/absence score. For the Daly River catchment, the number of species caught or observed was compared to 'expected' species richness developed from modelled data to produce an O/E score. No predictive model was available for the Fitzroy catchment. Instead, the fish species expected to occur at each site were derived from the literature, recent unpublished fish surveys and expert opinion. Fish assemblage data was recorded from 41 sites in the Daly River and 22 sites in the Fitzroy River.

The exotic fish and aquatic weed subindices were a measure of presence of exotic species. Opportunistic observation of aquatic vegetation was undertaken in both the Daly River and Fitzroy river catchments. In both catchments, knowledge of aquatic weed species and their identification and distribution was limited. Where possible, aquatic weeds were identified as either native or exotic, based on field identification and local knowledge.

For each of the three subindices (macroinvertebrates, fish and aquatic weeds) site scores were averaged for each stream order and weighted for contributing length of total stream network to produce an SWMA subindex score. Integration of SWMA subindex scores were then integrated to produce an aquatic biota score, using equal weighting (40% each) for fish and macroinvertebrates, with the aquatic weeds subindex assigned a lower weighting (20%), as field results were derived from opportunistic observations and basic assumptions.

FARWH scores for each subindex, and the final integrated aquatic biota score are provided below (Table 1.3).

Table 1.3:FARWH scores for land use, fire and the final catchment disturbance score calculated for the Daly and Fitzroy river catchments.

Subindex	Daly River		Fitzroy River
	Developed	Undeveloped	
Macroinvertebrates	0.83	0.86	0.87
Fish	0.64	0.96	0.87
Aquatic weeds	1.0	1.0	1.0
Aquatic biota score	**0.79**	**0.93**	**0.86**

Integration of theme scores

To provide an overview of river condition, an overall FARWH score was calculated from the six theme scores. Advantages of calculating a final score include the ability to rapidly compare SWMAs across regions and identity those catchments that are close to reference condition or degraded to some degree. Disadvantages of using a final score are that low-scoring themes may be masked by themes that score highly. It is therefore critical, especially from a management perspective, that subindex scores also be reported and considered in the context of the final SWMA score.

The six FARWH themes (Table 1.4) were integrated to give a final score for the SWMA using standardised Euclidean distance. Final FARWH scores for the Daly River catchment were **0.83** and **0.86** for the developed and undeveloped stratified zones and **0.85** for the entire SWMA. The final FARWH score for the Fitzroy catchment was **0.78** (Table 1.5).

Table 1.4: Integration of the six FARWH themes to a final FARWH score for the 'developed' and 'undeveloped' zones, and the entire Daly River SWMA.

Theme	Developed Zone	Undeveloped Zone	Daly River SWMA
Catchment disturbance theme	0.73	0.82	0.80
Hydrological disturbance theme	0.96	0.96	0.96
Water quality theme	0.91	1.00	0.96
Physical form theme	0.86	0.82	0.84
Fringing zone theme	0.83	0.77	0.80
Aquatic biota theme	0.79	0.93	0.86
FARWH score (0–1)	**0.83**	**0.86**	**0.85**

Table 1.5: Integration of the six FARWH themes to a final FARWH score for the Fitzroy River SWMA.

Theme	Score (0–1)
Catchment disturbance theme	0.71
Hydrological disturbance theme	0.98
Water quality theme	0.71
Physical form theme	0.85
Fringing zone theme	0.72
Aquatic biota theme	0.90
FARWH score (0–1)	**0.78**

Table 1.6 presents results of the desktop trials of FARWH in the Darwin Harbour and Ord River catchments. Results from this field study are also included; however, care should be taken when comparing scores between SWMAs, as methods used were in developmental stages and relied on data from a variety of sources not designed for catchment assessments. Also, aggregation methods may differ within themes (see individual theme chapters in this report and Dixon et al. (2009). An alternative method of integrating theme scores is to simply calculate the mean. The difference in final FARWH scores is minor (0.01–0.02) when compared to the recommended standardised Euclidean distance method. Land and water managers may be more receptive to using a mean score when interpreting the results, rather than the more complex Euclidean method.

Table 1.6: Theme scores for all trial SWMAs used in this report and the desktop trial of FARWH (Dixon et al. 2009).*

Theme	Daly: Developed	Daly: Undeveloped	Daly River	Fitzroy River	Darwin Harbour	Ord River
Catchment disturbance	0.73	0.82	0.80	0.71	0.87	0.85
Hydrological disturbance	0.96	0.99	0.96	0.98	0.84	0.81
Water quality	0.91	1.00	0.96	0.71	0.89	0.74
Physical form	0.86	0.82	0.84	0.85	0.95	0.73
Fringing zone	0.83	0.77	0.80	0.72	0.84	0.87
Aquatic biota	0.79	0.93	0.86	0.90	0.67	0.85
(a) FARWH (Euclidean Distance)	**0.83**	**0.86**	**0.85**	**0.78**	**0.82**	**0.80**
(b) FARWH (Mean)	**0.85**	**0.89**	**0.87**	**0.81**	**0.84**	**0.81**
Difference between (a) and (b)	0.02	0.03	0.02	0.02	0.02	0.01

* Final FARWH scores are calculated using standardised Euclidean distance. An alternative integration method using the mean of theme scores is also included for comparison. Note: methods used for each theme differ between SWMAs*.*

Testing of indicators to disturbance

The objective of this chapter was to test the response of riparian, water quality and biotic indicators to a gradient of catchment disturbance. Natural variability in broad landscape features among subcatchments in the wet/dry tropics was investigated using data from the Daly River. Landscape features were shown to vary among subcatchments and highlighted the need to identify appropriate reference conditions at the subcatchment scale at least.

The level of catchment disturbance was also assessed using a variety of existing databases and from field assessments of cattle impact on the riparian and stream habitats. This identified a gradient of disturbance among sites that reflected both the amount of land area cleared and cattle impacts in the riparian zones.

The sensitivity of FARWH indicators to the disturbance gradient was examined for fish, macroinvertebrates, metabolism and riparian vegetation. Main findings of the sensitivity analyses were:

- **Fish** and **macroinvertebrates (Daly River).** Modelling did not provide unambiguous evidence that any of the four biological indicators (fish community structure, macroinvertebrate community structure, fish richness and chironomid richness) responded to a gradient of disturbance. Potential explanations for these results include deficiencies in study design, predictive models, quantification of the disturbance gradient and fauna tolerance.

- **Metabolism (Daly River).** A decrease in the maximum dissolved oxygen deficit caused by cattle access to streams is not evident from the data, though there is evidence that the size of upstream pools has an influence.
- **Riparian vegetation (Daly River).** There is no strong evidence that riparian condition is affected by cattle disturbance using TRARC. This implies that disturbance is either minor or not detectable by TRARC.
- **Water quality (Fitzroy River).** Water quality attributes were largely insensitive to broad categories of cattle disturbance, and a pressure/condition gradient in the Fitzroy River catchment. These analyses highlighted the need to undertake further investigation on the natural temporal and spatial variability of water quality within the Fitzroy catchment.
- **Fish and macroinvertebrates (Fitzroy River).** Fish and macroinvertebrate scores showed a significant relationship to the pressure/condition score and increasing fishing pressure. The existence of multiple, scale-dependent mechanisms, potentially nonlinear responses of biota to disturbance, and the difficulties of separating current from historical effects can make it difficult to establish relationships between disturbance and ecosystem health indicators or to diagnose the specific sources or mechanisms of human impact.

The absence of, or weak relationships between the biotic indicators and measures of river health, may be due to a negligible or low level of impact, insensitivity of the indicators to low levels of impact, and matters concerning the analysis of the data and its design. These sensitivity analyses highlight the need for investigation of indicator sensitivity and detection thresholds for future river health monitoring in the wet/dry tropics.

Overall discussion

The FARWH scores for the Daly, Darwin Harbour, Fitzroy and Ord catchments were approximately **0.8**. This indicates that these rivers are not pristine or undisturbed, but better in comparison to many other Australian catchments. A key recommendation from these FARWH trials is that the primary objective of future river health monitoring in catchments in the wet/dry tropics should be the *early detection of river health degradation*. This will provide managers time to prevent further degradation, and foster a philosophy of *prevention* rather than *restoration* in river health monitoring. This objective has significant implications for the application of river health monitoring in general for the wet/dry tropics, and FARWH specifically.

River health assessment, and sample site (reach) data collection in the wet/dry tropical catchments needs to contend with remoteness, difficulty of access, requirements for landholder permission and participation, contrasting seasonal river conditions and, sometimes, poor river knowledge (such as the persistence of dry season flows). These constraints prevented the randomised selection of sample sites and resulted in an uneven distribution of sample sites for each stream order. Low-order streams were under-represented, though there is evidence to suggest that these streams may be more susceptible to impacts from cattle and feral animal disturbance.

The objective to detect early stages of river health degradation reflects that affected sites may not vary much from reference condition, and emphasises the requirement for sound knowledge about the relationships between reference condition and river health. This FARWH trial has highlighted the paucity of knowledge about reference condition in the wet/dry tropics, the cornerstone of FARWH. We recommend that reference condition and knowledge of its natural variability requires further research to enable a more accurate river health assessment.

To detect small deviations from reference condition and minimise type 1 errors that conclude there is no impact when an impact does exist, a large number of sample sites are required, especially for the huge SWMAs of the wet/dry tropics. A more manageable number of sites, however, could be selected if river health assessments focused on SWMA subcatchments rather than the whole SWMA.

Another foundation of river health assessment, and FARWH, is that theme indicators are responsive to anthropogenic disturbance. This trial demonstrated this for the hydrology theme, using the FSR procedure. Indicators for the physical form, fringing zone, water quality and aquatic biota indices, however, were not shown to be unambiguously responsive to the levels of impact, based on catchment and finer-scale measures of disturbance. We recommend that, to achieve the early detection of river health degradation, thresholds of indicator responsiveness and their relationships to degradation be investigated further.

The primary recommendation of the trial is that a two-tiered approach be undertaken to assess river health in SWMAs of the wet/dry tropics. The first tier can be achieved at the SWMA scale and would comprise the catchment disturbance theme, using spatial data sets and supported by ancillary information—for example, cattle-stocking rates, feral animal numbers and the number of significant point sources of pollution. This would provide an assessment of the catchment pressures on river health, and could be included in the hydrologic theme.

The second tier would comprise river health case studies, conducted at a small scale, and include reference sites matched to test sites. This tier would provide site/reach scores for the remaining themes. These case studies would provide early warning of river health degradation and be undertaken in the context of knowledge of catchment-wide pressures on river health. Based on the relationship between the disturbance and river health degradation, the results from such case studies could be extrapolated to the SWMA to be combined with the catchment and hydrologic disturbance themes for a FARWH SWMA score.

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2 Introduction

2.1 Background

The tropical rivers of northern Australia are internationally recognised for their high ecological and cultural values. Unlike many other tropical systems and their temperate Australian counterparts, Australian tropical rivers have largely unmodified flow regimes and are comparatively free from the impacts typically associated with intensive land use (see Douglas et al. 2005). The wet/dry tropical climate of Australia is typically described as a sequence of predictable, annual periods of ‘flood’ (wet season) and ‘drought’ (dry season). These extremes and the vastness of the region pose both scientific and practical challenges for assessing river heath.

Not only does the climate of the wet/dry tropics differ fundamentally from temperate Australia, but the nature of environmental impacts on the aquatic environment also differs. The region has experienced very little intensive development, with cattle grazing of native pastures the dominant land use. Although there are very few dams or weirs and only a small proportion of the region’s vegetation has been cleared, river health is threatened by a multitude of often-escalating, pervasive processes. For example, more frequent and intense fires have decreased the cover of riparian vegetation and resulted in a significant increase in soil erosion and nutrient inputs to rivers (Townsend and Douglas 2000, 2004). Weed invasion alters fire regimes and prevents the recruitment of riparian vegetation, and feral animals (e.g. feral pigs and cattle) foul dry season (often ‘refugial’) waterholes, uproot native vegetation and increase bank erosion.

Recent research focused on ecological processes in Australian tropical systems has derived general principles that both characterise tropical rivers of northern Australia and have important implications for the assessment of river health and subsequent management of environmental issues (modified after Douglas et al. 2005):

- The seasonal hydrology of Australian tropical systems is a strong driver of ecosystem processes and food-web structure.
- Hydrological connectivity is largely intact and underpins important terrestrial–aquatic food-web subsidies.
- River and wetland food webs are strongly dependent on algal production.
- A few common macro-consumer species have strong influence on food webs.
- Omnivory is widespread and food chains are short.

Based on these general principles of how Australian tropical ecosystems function, river health methods and indices developed for temperate Australia need modification and testing for valid application in the wet/dry tropics. For example, a rapid assessment protocol for riparian condition, developed in temperate Australia, required considerable modification before it was suitable for application in the wet/dry tropics (the Tropical Rapid Appraisal of Riparian Condition—TRARC) so that it could detect more subtle changes beneath the riparian canopy. Other approaches and indices may also need to be modified to accommodate the relatively limited funds available for river health assessment relative to the vast size of the region.

River health assessments in Australia are founded on a reference condition (e.g. often ‘least impacted’ or control), but in some parts of Australia (e.g. western New South Wales) there may be no suitable sites. In contrast, although there are potential suitable reference sites in the tropical regions of the Northern Territory (NT), Western Australia (WA) and Queensland (Qld), reference condition is not regularly monitored, generally because of insufficient funds, remoteness, restricted wet season access and the often ad hoc nature of Australian tropical research.

2.2 FARWH need and development

Australian states and territories are signatories to the National Water Initiative (NWI), the progress of which is assessed by the National Water Commission (NWC). An important NWI outcome is the delivery of a nationally compatible market, with a regulatory and planning-based protocol for managing surface and groundwater resources for rural, social and environmental outcomes. The Framework for the Assessment of River and Wetland Health (FARWH) is funded by the Australian Government’s $250 million Raising National Water Standards (RNWS) program. This program supports the implementation of the NWI by funding projects that are improving Australia’s national capacity to measure, monitor and manage our water resources.

During 2006, the *Australian Water Resources 2005 Discovery Phase* (AWR 2005) investigated the availability of data for a national river health assessment. This process showed sufficient data in some regions through programs such as:

- Victorian Index of Stream Condition
- Victorian Index of Wetland Condition
- Tasmanian Conservation of Freshwater Ecosystem Values Framework
- Queensland Wetlands Program.

However, this assessment found that, typically, data was patchy, with limited capacity to develop a national approach for river health assessment or for linkages to state of the environment reporting. Consequently, a national framework for river heath assessment— the FARWH—was developed. .

This document constitutes the field trial for the NWC project, Development and implementation of the Framework for the Assessment of River and Wetland Health (FARWH) to Rivers in the Wet/Dry Tropics of Northern Australia. The project is managed by the Tropical Rivers and Coastal Knowledge research hub (TRaCK), which includes the University of Western Australia (UWA), as lead for Western Australia, Charles Darwin University (CDU), for the Northern Territory and Griffith

University, for Queensland, in association with:

- NT Department of Natural Resources, Environment, the Arts and Sport (NRETAS)
- WA Department of Water (DOW)
- Qld Department of Environment and Resource Management (DERM)
- eWater CRC.

This report aims to summarise the trials of the FARWH in two catchments of northern Australia, the Daly River (NT) and the Fitzroy River (WA). In addition to trialling the framework, and to field methods and data analyses, the report investigates the sensitivity of indicators of river health to a gradient of localised pressures, especially land use, and cattle and feral animal activity.

Field trials took place between June and October 2009 by researchers from the TRaCK research consortium. This project engaged NT and WA stakeholders to undertake fieldwork and associated analyses. The FARWH has previously been trialled in the Northern Territory and Western Australia (desktop trials for Darwin Harbour and Ord River catchments (Dixon et al. 2009; see Section 2.4 below), Victoria and Tasmania, and is currently being trialled in Queensland, South West Western Australia and New South Wales (wetlands).

Throughout the report, we refer to the ‘tropical FARWH’. This is shorthand for the wet/dry tropics, as the project does not include the wet tropics of eastern Australia, nor the arid tropics of inland Australia.

2.3 **Structure of FARWH**

The FARWH comprises six river health themes that are compared to reference condition to produce an index between 0–1, where a score of 1 implies excellent condition or health, and 0 implies severe ecological degradation:

1. Catchment disturbance
2. Hydrological disturbance
3. Water quality
4. Physical form
5. Fringing zone
6. Aquatic biota.

Each theme comprises subindices, using the same referential and scoring approach. With assessment indicators rated against a 0–1 scoring range, comparison across catchments with naturally contrasting river characteristics should be possible. To help standardise approaches for assessing river health, the NWC (2007) has provided recommendations and examples of indicators and subindices to trial in the framework, including definition of stream reaches and methods to integrate and aggregate assessment components.

2.4 **Desktop trials of FARWH**

Between December 2008 and April 2009, TRaCK researchers engaged NT and WA stakeholders to undertake a post hoc analysis of existing stream and catchment datasets for Darwin Harbour (NT) and the Ord River (WA) catchments—hereon referred to as the desktop trials (Dixon et al. 2009). Trials of the FARWH in the Darwin Harbour catchment focused on sampling efforts in 2005. Data for the Ord River study were spread across several years (1998–2006) due to the ad hoc nature of sampling events. As an overview, the desktop trials study discussed the following:

Surface water management area (SWMA)

- In the Darwin Harbour catchment, the SWMA boundary was modified to reflect the current interests of the NT Government.
- In the Ord River catchment, the SWMA boundary better reflected management interests, but included a river from another system.

Reach identification

- Because of the low relief of the Darwin region, National Land and Water Resources Audit (NLWRA) FARWH reaches were inadequate. Stream order was used for this study.
- NLWRA FARWH reaches in the Ord catchment were suitable for this study.

Catchment disturbance theme

- The addition of a fire subindex (catchment and river corridor) worked well in both catchments and was a simple metric to calculate. Weightings were applied to 'month of fire'.
- Using a revised weighting system for impacts of land uses, the land-use subindex was also effectively applied to both catchments.

Hydrological disturbance theme

- This study was the first to use the Flow Stress Ranking (FSR) procedure in the wet/dry tropics. The FSR procedure produced results with reasonable confidence when applied to modelled concurrent datasets.
- Many stream networks in both catchments had no hydrographic data, thus expert rules based on land use were used.

Water quality theme

- An interim scoring system was devised for nine water quality parameters. Scores were based on the natural range of reference sites and expert opinion of perceived levels of degradation.
- The Darwin Harbour and Ord catchments water quality bands varied due to differences in reference condition.
- Further literature research needs to be undertaken to increase understanding of

ecological thresholds, which in turn will help assist development of the scoring bands.

- Sampling efforts were not designed to give a catchment-wide assessment of health. As a result, an uneven distribution of sites per stream-order length may have biased the final result.

Physical form theme

- The bank stability subindex worked well in both catchments and provided detailed site-scale measures of erosion. However, sampling efforts were not designed to give a catchment-wide assessment of health.
- The connectivity subindex was restricted in its use due to the absence of suitable data for small structures. If this subindex is to be developed further, field trials and ground-truthing of available data will be required.

Fringing zone theme

- Scores for TRARC were successfully modified to meet the requirements of FARWH. However, sampling efforts were not designed to give a catchment-wide assessment of health.
- As remote sensing was not used in these trials, TRARC is well suited to both catchments as an on-ground measure of riparian condition.

Aquatic biota index

- Suitable datasets varied between catchments, thus different metrics were trialled.
- Macroinvertebrate AUSRIVAS scores were used in both catchments. The data used was unevenly distributed across the catchment and stream orders.
- Aquatic weeds and exotic fish were both simple measures used in the Darwin Harbour catchment. Although derived from subjective data, they are intended to set the grounds for future development of these metrics.
- In the Ord River catchment, fish data was suitable to derive four metric scores—species richness, diversity, nativeness and connectivity. However, results should be interpreted with care, due to the temporal variation of datasets, and the uneven distribution of sites within the catchment.

Suitability of the FARWH in the Darwin Harbour and Ord River catchments

- The data used to assess many of the FARWH themes was collected during specific ecological or monitoring studies. As such, sampling effort was not designed to provide a catchment-wide assessment of river health, but rather provided an uneven distribution of data across each of the catchments and at variable timescales. Consequently, this limited the assessment of river health at the SWMA scale, and results should be interpreted with care.
- The original sampling design/s did not consider point-source impacts.
- Both catchments are considered semi-developed when compared to other

regions across northern Australia. With further research of scoring bands and a specific sampling design, we conclude that the FARWH is a reasonable approach to use in the Darwin Harbour and Ord River catchments.

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3 Design of FARWH trials

3.1 Surface water management areas

Surface water management area (SWMA) boundaries were first created by Geoscience Australia in 2000 and used in the National Land and Water Resources Audit (NLWRA) (Norris et al. 2001). The desktop trial of the wet/dry tropical FARWH (Dixon et al. 2009) recommended that the SWMA boundaries be revised to match the current interests of government land and water managers. Boundaries needed to capture development impacts, as there was a risk that the current approach did not identify resource over-allocation or significant environmental disturbance. This was especially apparent across northern Australia, which typically has very large SWMAs and increasing development pressures. For example, the single SWMA of the Daly and Fitzroy river catchments are comparable in size to the 20 combined SWMAs of Tasmania (Table 3.7). An important component of the tropical FARWH, clearly stated by state/territory government stakeholders, was the need to calculate subcatchment FARWH scores. The current level of development across northern Australia is typically represented by a disturbed subcatchment surrounded by a large area of relatively undisturbed catchment.

Table 3.7 Comparative sizes of SWMAs for three tropical FARWH trial catchments and the states of Victoria and Tasmania.

Region	No. of SWMAs	Area (km^2)
Daly River	1	52 647
Ord River	1	55 477
Fitzroy River	1	80 106
State of Tasmania	20	62 000
State of Victoria	32	229 532

3.1.1 Daly River SWMA

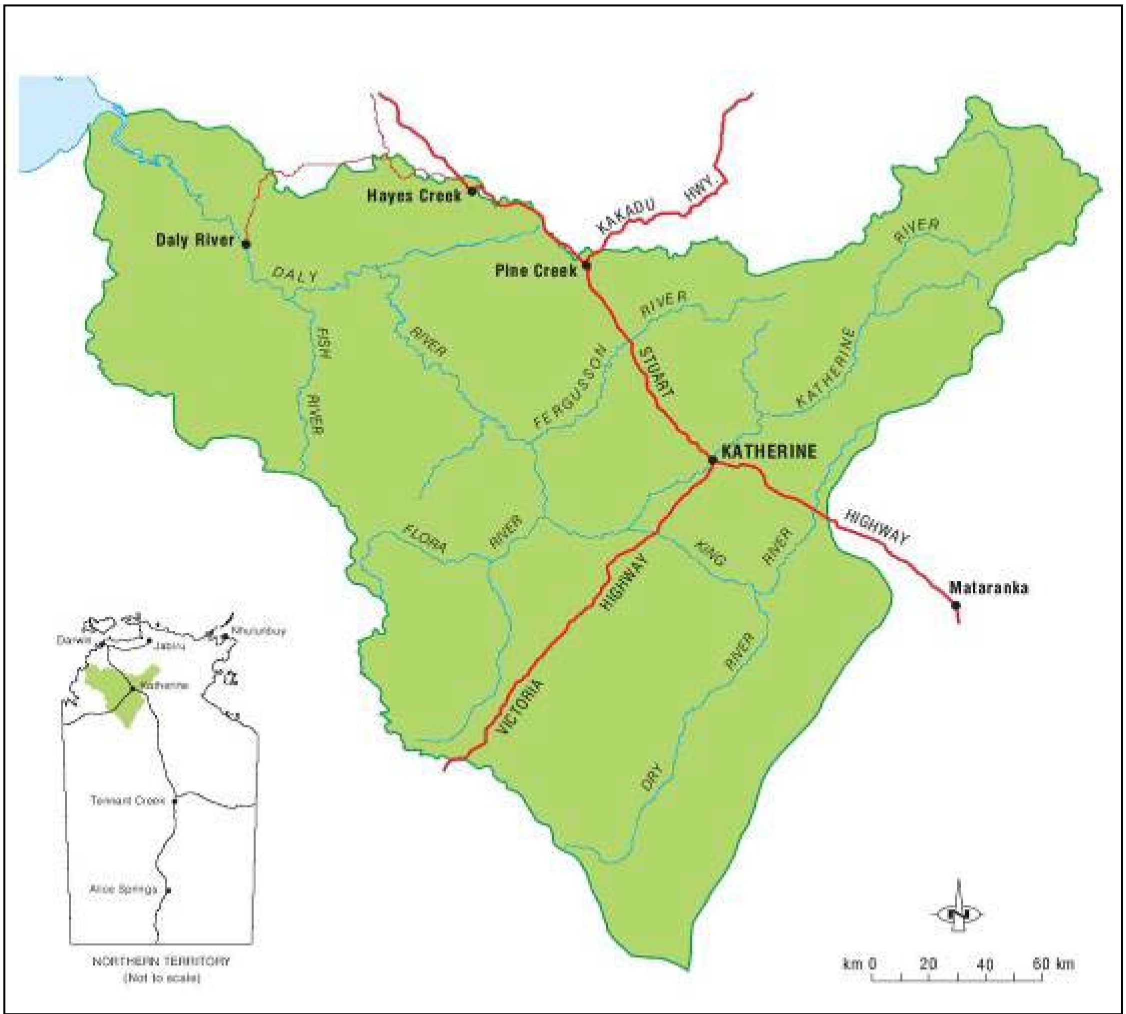
Catchment description

The Daly River catchment is located approximately 200 km to the south of Darwin and includes the townships of Katherine, Pine Creek and Nauiyu (Daly River township). The catchment area is approximately 52 647 km^2. Major rivers in the catchment are the Katherine, Dry, Flora, Fergusson, Douglas, Fish, and Daly Rivers (Figure 3.1). The main aquifers are the Cretaceous sandstone, Oolloo dolostone, and the Tindall limestone aquifers. Annual rainfall over the catchment averages approximately 1000 mm, with 90% falling between November and March (Jolly 2002). As a result, river and stream flow is highly seasonal, with many streams ceasing to flow in the dry season (i.e. seasonally flowing). The Daly, Katherine, Douglas and Flora rivers are perennial, because they intercept groundwater that maintains surface flows over the dry season.

The median annual stream flow for the Daly River recorded at Mount Nancar gauging station for the 30-year period from 1970 to 2000 was 6 200 000 megalitres (ML). Groundwater discharge contributes an estimated 600 000 ML per year (Daly Region Community Reference Group 2004).

In 2008, the two major land uses within the catchment were grazing of native vegetation (50%), and conservation and natural environments (42%). Other land uses include grazing of modified pastures, cropping (e.g. hay, silage, peanuts) and horticultural production (e.g. mangoes). Conservation parks and reserves make up roughly 5 500 km^2 (Daly Region Community Reference Group 2004). These areas attract a large number of visitors to the region and support a variety of cultural and recreational activities. The region is renowned for its near-pristine waterways and relatively undisturbed environment compared to southern Australia.

Figure 3.1: Daly River catchment (Source: NRETAS; from Risby et al. 2009).



Three types of cattle grazing occur in the Daly River catchment:

- controlled paddock grazing (fenced paddocks on land cleared for improved pastures)
- controlled open grazing (fenced or unfenced paddocks on mostly uncleared native savanna)
- semi-controlled wild grazing (usually unfenced on uncleared savanna)

All types of grazing in the catchment typically have unrestricted access to the riparian zone and river channel. Where fences exist, they are primarily for paddock delineation and mustering thoroughfares (cattle lanes). Except for riparian conservation zones, fencing does not exclude stock from waterways. Cattle congregate under the shade of the riparian canopy and use sections of the bank to access drinking water or for channel crossings. These activities are concentrated at suitable access/crossing points (shallow reaches with gentle banks), with a network of linking tracks throughout the riparian corridor.

Cattle activity on properties with controlled paddocks is more abundant in the early dry season (June–August). After August, pastoralists muster the majority of stock to yards for either shipment to floodplain paddocks (and then to market) or for reallocation to wet season paddocks (higher ground) as continued breeding stock. Cattle activity in the riparian zone and channel is minimal in the late dry season.

Region of management priority

The region of highest terrestrial and water management priority in the Daly River catchment is an area identified as having agricultural potential, based principally on soil suitability (termed the 'Potential Agricultural Zone'; Figure 3.2). This area is most developed (based on the proportion of native vegetation cleared), though some subcatchments remain in a largely undeveloped (uncleared) state and can be considered to be in reference condition but not pristine (cattle grazing often occurs on uncleared lands, with unrestricted access to waterways).

To ensure FARWH is meaningful to NRETAS and does not simply report a single FARWH score for the whole catchment, the Daly River catchment was divided into two strata: 1) 'developed' and 2) 'undeveloped' zones (Figure 3.2). NRETAS's priority lies with the developed areas, because this is where landholders and government agency management is most active. The remainder of the catchment is still of interest, especially in terms of managing fire, weeds and feral animals, but does not include much cleared land.

To select developed areas within the Potential Agricultural Zone, a minimum threshold for clearing of native vegetation was defined for each of the subcatchments. This criterion was selected post hoc and set at 7.5% of the subcatchment cleared. The resulting 'developed zone' forms 19% of the entire Daly River Basin (Table 3.8).

This project has reported the FARWH for both the developed and undeveloped zone of the Daly River catchment and then aggregated the results to an SWMA level. Sampling effort was biased to the collection of data from the developed catchments because it was believed these would have the greatest variability in river health and therefore require more intensive sample collection relative to undeveloped catchments. These sites also contributed to a study that investigates the responsiveness of indicators to a gradient of localised disturbance (see Chapter 11, 'Testing of indicators to disturbance').

Figure 3.2: Daly River catchment stratified into two zones: developed and undeveloped. The developed region lies within the Potential Agricultural Zone.

Table 3.8: Comparative sizes of the 'developed' and 'undeveloped' zones within the Daly River catchment.

Zone	Area (km^2)	%
Developed	10 095	19
Undeveloped	42 552	81
Total	**52 647**	**100**

3.1.2 Fitzroy River SWMA

The Fitzroy River catchment boundary matches the NLWRA SWMA-assigned boundary. The Fitzroy River is one of Australia's largest unregulated rivers, with the catchment spanning the Kimberley from east to west and traversing a variety of geological and climatic gradients. The headwaters of the Fitzroy River, in the north and east of the catchment, receive flow from the Hann, Adcock, Manning and Little Fitzroy rivers. These tributaries drain primarily rocky, bedrock country. The Margaret River drains the upper south-east catchment, and receives water from the Mary, Glidden, O'Donnell and Leopold rivers. This drier and low-gradient country is characterised by wide channels of permeable sands, occasionally constricted by gorges (i.e. the Dimond and Margaret River gorges) with the Margaret River joining the Fitzroy River downstream from Gieke Gorge. Downstream of this confluence the remaining 300 km of river is characterised by a shifting, sandy floodplain with substantial branching and anabraiding (Storey et al.. 2001). Major lower catchment tributaries (downstream of the Margaret River confluence) include the Christmas and Geegully creeks, which flow into the Fitzroy before it discharges into King George Sound.

In addition to variations in geology, there is also a strong north–south rainfall gradient. Mean annual rainfall decreases from 464.5 mm/yr (Halls Creek Station) in the south-eastern Christmas Creek catchment to a mean annual rainfall of 888 mm/yr (Mount Barnett Station) in the northerly Hann River catchment. This coincides with a runoff coefficient, decreasing from 25 to 3 per cent of rainfall in the same direction.

River valleys are frequently flooded during the wet season and the region is groundwater-dependent in the dry. Pools are maintained into the dry season via shallow subsurface flow, with sand bars partitioning the rivers in the region.

3.2 Reach definition

3.2.1 Daly River

A stream network for the river health assessment of the Daly River catchment was created using the NLWRA reach network. These reaches have a minimum length of 5 km, a minimum catchment size of 50 km^2 and break where stream power doubles (based on gradient and catchment size). Reaches influenced by salt water, as indicated by the presence of mangroves, were removed from the FARWH trials. Reaches were added where previous monitoring had been conducted, and some reaches were realigned to match the 1:250 000 watercourse layer. In total there are 386 reaches (4744 km) within the Daly River catchment.

3.2.2 Fitzroy River

There were no NLWRA audit reaches available for the Fitzroy River field trials. A variety of techniques were trialled to assign reaches, based on stream order (1:250 000 watercourse layer) before a suitable replacement to the NLWRA reach network was developed.

Firstly, a number of alternative reach networks were assessed for their applicability to assign reach classifications for the Fitzroy River. The Northern Tropical Rivers study area classification by Saynor et al. (2008) produced a reach layer for the Fitzroy River catchment based on a geomorphic classification (1:2,000 000 scale *Atlas of Australia* soils). Using the 1:250 000 named and major stream layer, they delineated reaches based on landform, resulting in six of the 169 reaches with a mean reach length of 1.32 km (total length of stream network 8141 km—

Table 3.9). Based on the recommended minimum lengths of 5 km for the FARWH assessment (NWC 2007), this method produced inappropriate reach lengths for the field trials (reach lengths were considered too short ~1.3 km average).

Table 3.9: Reach classes developed by TRIAP for the Fitzroy River catchment. Average reach length is 1.3 km.

Geology class	No. of reaches	Total length (km)
Anabranching	2597	3631
Bedrock channels	532	607
Bedrock confined	2500	3134
Billabong/lake/swamp	4	6
Chain of ponds	10	40
Estuary	100	111
Floodout	13	40
Gully	6	24
Low sinuosity	187	175
Meandering	199	302
Non-channelised	21	72
Total	**6169**	**8141**

After investigating alternative methods of applying reach networks, an automated reach network was developed and considered suitable for this FARWH assessment. Reaches were broken at stream link and assigned a stream order, using the Strahler approach (Gordon et al. 2004): stream orders increase when two streams of the same order intersected. Using a 3-sec DEM and ArcMap 9.2 Hydro Tool extension, this method allowed for a relatively good match to the 1:250 000 watercourse layer. A minimum catchment area of 50 km was applied and provided a stream network at a resolution similar to the NLWRA reaches used for the Ord and Daly river catchments. The quality of this reach network was limited by the resources available and should not be used for any other applications outside FARWH without careful consideration.

The automated reach network developed for the Fitzroy River catchment resulted in a reach network of 11 900 km, with 50% first-order streams and stream orders up to six represented (Table 3.10). Because of the lower resolution of the automated stream network, the lower Fitzroy River is considered a sixth-order stream.

Table 3.10 Summary of reach network in the Fitzroy river catchment.

Stream order	Length (km)	No. of reaches
1	5904 (50%)	600
2	2813 (23%)	261
3	1872 (16%)	201
4	632 (5%)	71
5	225 (2%)	23
6	454 (4%)	35
Total	**11 900**	**1191**

3.3 Site selection

For the purpose of this study, a site is generally a 250–500 m section of stream that represents a FARWH reach. The terms ‘site’ and ‘reach’ may be used interchangeably throughout this report.

3.3.1 Site selection: Daly River

Perennial streams

Based on NLWRA-defined reaches (FARWH reaches), sites in the Daly River catchment were sampled during the dry season, between late June and early October. During this season, many streams cease flowing and become dry streambeds. This period was chosen for sample collection because the AUSRIVAS, Daly River Fish mmodel, and TRARC tools for river and riparian health assessment were developed for dry season data collection. It is also the season when rivers and streams are most accessible, and potentially the most vulnerable to disturbance, especially from point sources.

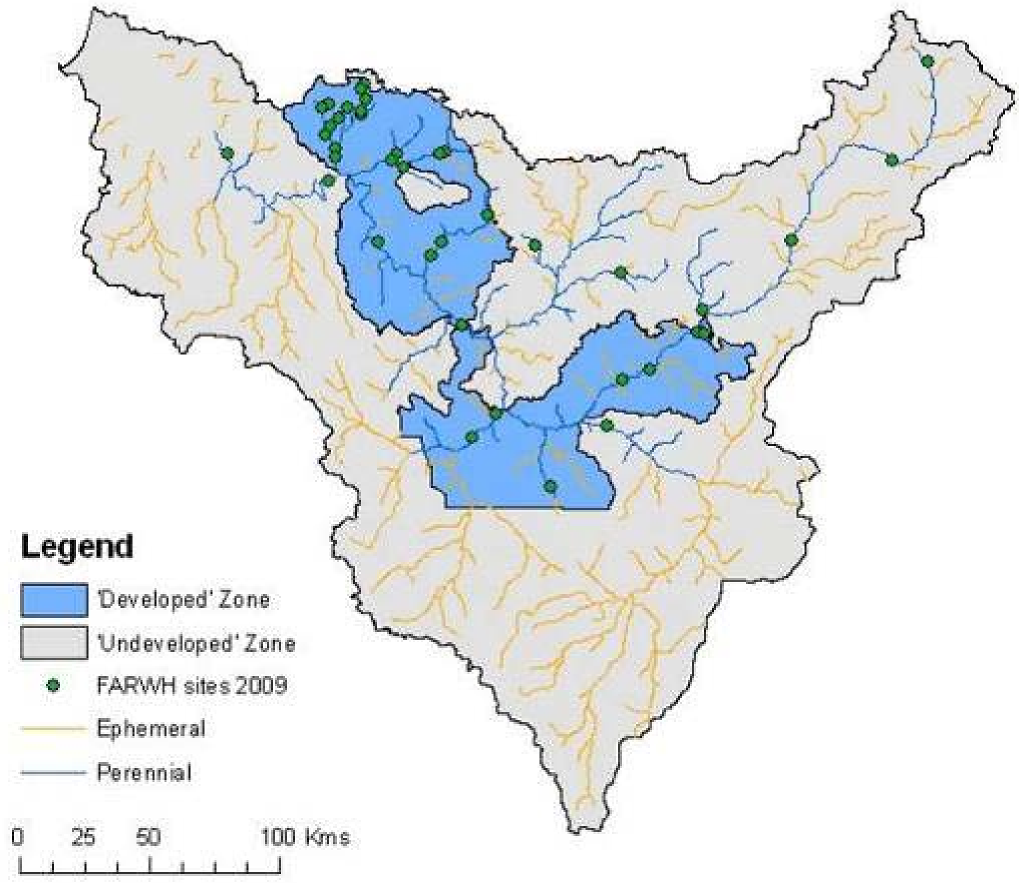
A high priority was placed on collecting aquatic biota data because it provides the most direct measure of river ecosystem health. The application of the FARWH to dry season health of flowing rivers and streams is easier to communicate and has greater credibility when it includes aquatic biota, but has meant the assessment did not address wet season river health.

The FARWH trial implemented in this project therefore evaluated the health of perennially flowing rivers for the most part (Figure 3.3), though some did cease to flow between September and October. As calculations of several FARWH subindices use the length of streams as a weighting factor, only perennial streams in the catchment were included in such computations, thus reducing the number of FARWH reaches and stream network in the catchment. Of the overall FARWH stream network, 1587 km (149 reaches; 39% of total length) were classed as perennially flowing (Table 3.11).

Perennial streams were defined as those flowing throughout the late dry season. Perennial reaches were identified by ground-truthing of the NRETAS perennial flow map (Tickell 2008). Using gauging data for major watercourses, this assessment indicates 856 km (2%) of the NLWRA stream network has flow above about 1 L/sec throughout the dry season. This layer provided limited information for tributaries. For example, the Green Ant Creek system (where monitoring effort was concentrated in this study) is not recognised as perennially flowing. We expanded this map to include streams observed to be flowing throughout the field trials. In total, 1587 km of the NLWRA reach layer were classed as ‘perennial’ (i.e. flowing during the dry season until at least September). This equates to 33% of the NLWRA reach network length (Figure 3.3; Table 3.11a). Of the perennial stream network length, 43% were located within the developed zone and 57% within the undeveloped zone of the Daly River SWMA (Table 3.12).

The NLWRA-reach network, however, omits low-order streams when compared with the 1:250 000 GIS layer (Table 3.5b). This FARWH assessment, therefore, under-represents small streams.

Figure 3.3: Perennial and ephemeral reaches of the FARWH stream network*.



***Reaches are defined in Section 3.2.1. A total of 41 perennial reaches were surveyed between June–October 2009 within the 'developed' and 'undeveloped' zones of the Daly River catchment.**

Table 3.11: (a) Proportion of perennial and ephemeral FARWH reaches in the Daly River catchment. Reaches are defined in Section 3.2.1.

	Perennial		Ephemeral		Total	
Stream order	Length (km)	No. of reaches	Length (km)	No. of reaches	Length (km)	No. of reaches
1	501 (31%)	43	2286 (73%)	174	2787 (59%)	217
2	379 (24%)	38	612 (19%)	44	991 (21%)	82
3	336 (21%)	40	194 (6%)	15	530 (11%)	55
4	120 (8%)	10	65 (2%)	4	185 (4%)	14
5	251 (16%)	18	0	0	251 (5%)	18
Total	**1587 (33%)**	**149 (39%)**	**3157 (67%)**	**237 (61%)**	**4744**	**386**

(b) Stream network for the Daly Catchment based on 1:250 000 topographic layer (Geoscience Australia).

Stream order	No. of reaches	Length of reaches (km)	Proportion of stream network
1	18 011	28 378	0.78
2	2901	3968	0.11
3	1675	2078	0.06
4	725	844	0.02
5	391	427	0.01
6	197	214	0.01
7	264	316	0.01
Total	24 164	36 225	1.00

Table 3.12: Perennial reaches in the developed and undeveloped' zones of the Daly River catchment. Reaches are mapped in Figure 3.3. Reaches are defined in Section 3.2.1.

PERENNIAL	Developed zone		Undeveloped zone	
Stream order	Length (km)	No. of reaches	Length (km)	No. of reaches
1	243	26	258	17
2	184	21	195	17
3	127	16	209	24
4	68	6	52	4
5	125	7	126	11
Total	**747 (47%)**	**76**	**840 (53%)**	**73**

Site selection

Sample-site selection in the Daly River SWMA met two broad objectives: 1) to provide data for the FARWH trial, and 2) to provide data to assess the impact of land use on river health indicators and metrics used by FARWH.

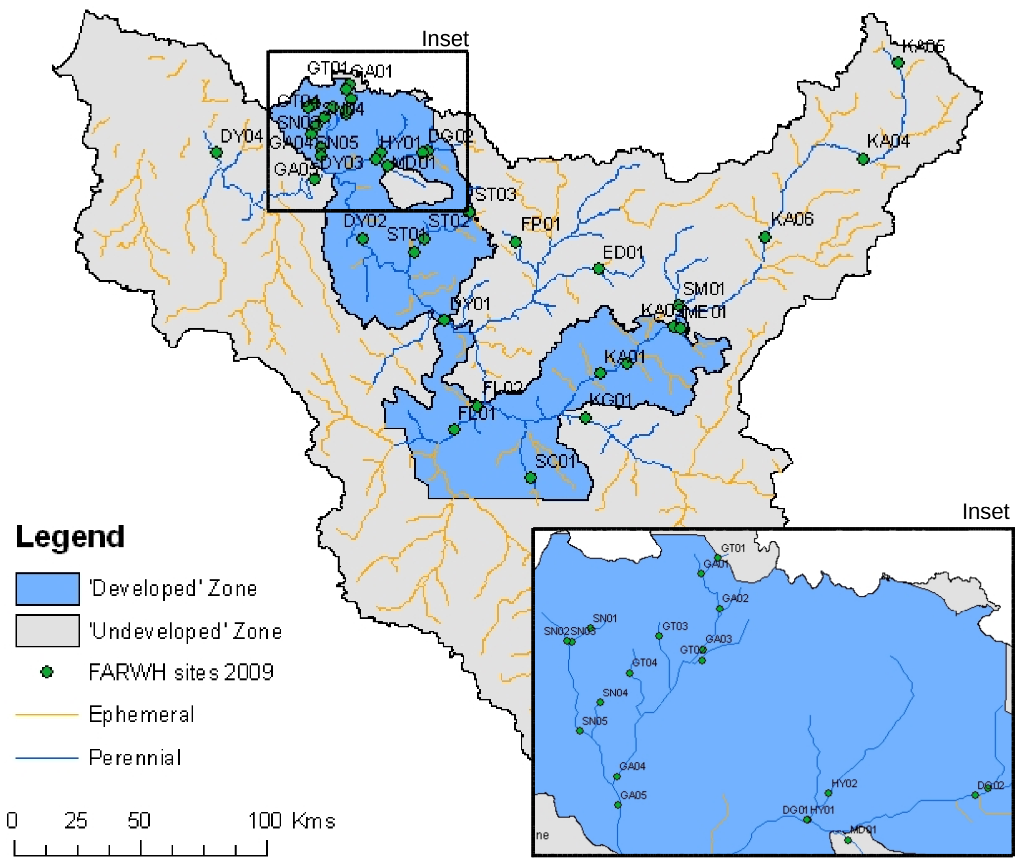
Samples sites were chosen according to following criteria:

- flowthrough most of the dry season, generally at least until September.
- accessible by four-wheel drive vehicle—only in remote locations was helicopter

access considered

- efficiency of determining site vehicle access—this favoured sites visited during the National River Health Program in the mid-90s, for which NRETAS provided access details
- consideration of the areas of priority management for NRETAS
- inclusion of a range of catchment land-use (principally grazing) intensities, as well as reference condition sites, which would permit an analysis of the relationship between indicator metric values and a gradient of disturbances.

Figure 3.4: A total of 41 perennial reaches were surveyed between June–October 2009 within the ‘developed’ and ’undeveloped’ zones of the Daly River catchment. Site coordinates and descriptions are listed in Appendix 13.1.



These criteria do not provide for randomly chosen sites, an objective of FARWH that meets the requirements of an unbiased data collection. Without considerably more knowledge about the duration of dry season flow and more resources to access sites in remote locations, the random selection of sites in the Daly River catchment was not practical if a large number of sites were to be sampled.

With the resources and time available to the project, we sampled 41 sites in the Daly River catchment (Figure 3.4; see Appendix 13.1 for coordinates and site description). These were concentrated in the Douglas–Daly region, where subcatchments had a range of cleared land area. While the Katherine area is of management interest to NRETAS, there are few perennially flowing rivers. In general, sites were chosen that permitted all (or most) FARWH themes to be sampled to maximise the efficiency of fieldwork.

Table 3.13: FARWH indicators assessed at 41 sites in the Daly River catchment, July–Oct. 2009.*

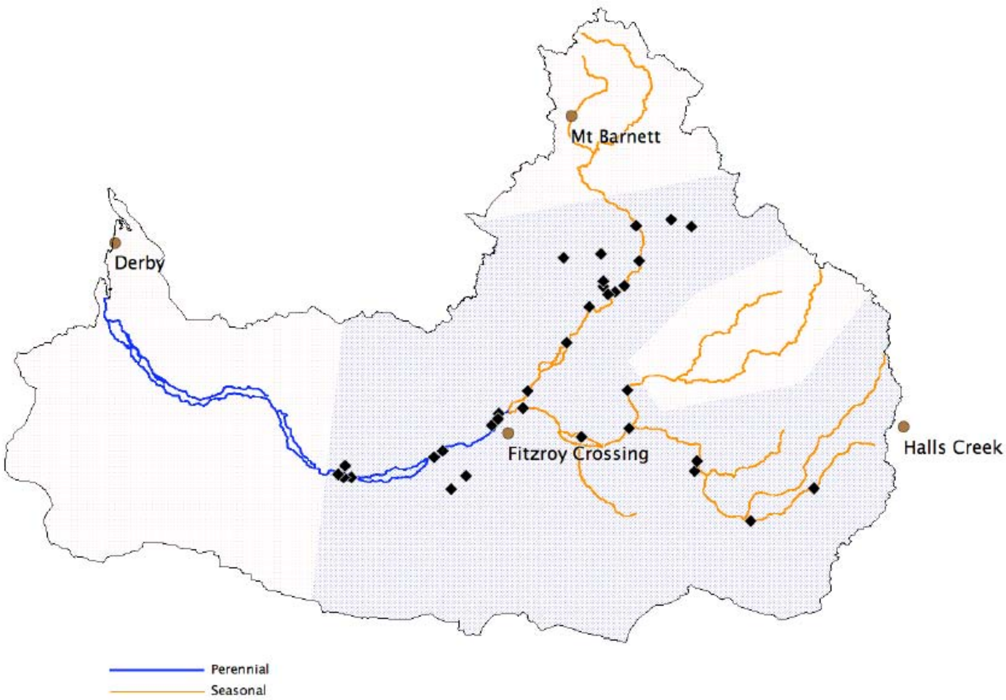
	Water quality	Physical form	Fringing zone	Aquatic biota			Additional
Site	**Phys/chem & nutrients**	**Bank stability**	**Riparian**	**Bugs**	**Fish**	**Aquatic weeds**	**Metabolism & feral animal impact**
DG01	+	+	+	+	+	+	+
DG02	+	+	+	+	+	+	+
DP01	+	+	+	+	+	+	+
DY01	+	+	+	+		+	
DY02	+	+	+	+		+	
DY03	+	+	+	+		+	
DY04	+	+	+	+		+	
ED01	+	+	+	+	+	+	+
FL01	+	+	+	+		+	
FL02	+	+	+	+		+	
*FP01	+	+	+	+		+	+
GA01	+	+	+	+	+	+	+
GA02	+	+	+	+	+	+	+
GA03	+	+	+	+	+	+	+
GA04	+	+	+	+	+	+	+
GA05	+	+	+	+	+	+	+
GT01	+	+	+	+	+	+	+
GT02	+	+	+	+	+	+	+
GT03	+	+	+	+	+	+	+
GT04	+	+	+	+	+	+	+
HY01	+	+	+	+	+	+	+
HY02	+	+	+	+	+	+	+
KA01	+	+	+	+		+	
KA02	+	+	+	+		+	
KA03	+	+	+	+		+	
KA04	+	+	+	+		+	+
KA05	+	+	+	+		+	+
KA06	+	+	+	+		+	+
KG01	+	+	+	+		+	
MD01	+	+	+	+	+	+	+
ME01	+	+	+	+		+	
SC01	+	+	+	+		+	
SM01	+	+	+	+		+	+
SN01	+	+	+	+	+	+	+
SN02	+	+	+	+	+	+	+
SN03	+	+	+	+	+	+	+
SN04	+	+	+	+	+	+	+
SN05	+	+	+	+	+	+	+
ST01	+	+	+	+	+	+	+
ST02	+	+	+	+	+	+	+
**ST03	+	+	+	+		+	+

* This table does not include desktop-based assessments of Catchment Disturbance, Hydrology and Connectivity. Sites are shown in Figure 3.4 and coordinates in Appendix 13.1.
** Dried up during late dry season

3.3.2 Site selection: Fitzroy River

The remoteness of sites, rough terrain, as well as requirements for community engagement (discussed below) represented an important limitation on site selection and data collection for the Fitzroy River field trials. The field trials were conducted under a research agreement between TRaCK and the Kimberley Land Council. The agreement required extensive engagement and collaboration with both pastoralists and traditional owners. It required the FARWH field team to seek approvals for conducting field sampling on traditionally owned land and pastoral leases, and collaboration (particularly with traditional owners) for data/sample collection.

Figure 3.5 A total of 37 reaches were surveyed between June–Oct. 2009 within the Fitzroy River SWMA.*



***Site coordinates and descriptions are listed in Appendix 13.2. Major streamlines are shown as perennial or seasonal (with permanent pools). Dark and light shaded areas represent access granted or declined respectively.**

These practicalities resulted in the largely opportunistic selection of sampling sites, rather than a randomised approach. For example, many of the sites where we were permitted to conduct fish surveys were identified as important traditional fishing holes. Finally, the requirement for research to be conducted under research agreements also limited access to some areas of the Fitzroy River catchment. Despite substantial negotiation, approval from traditional owners of the lower floodplain reaches could not be obtained and no field trials were undertaken in tributaries in the far north-east of the catchment (Figure 3.5).

Field trials in the Fitzroy River catchment focused on the sensitivity of indicators to

Table 3.14: FARWH indicators assessed at 37 sites in the Fitzroy River catchment, June–Oct. 2009.*

	Water Quality	Physical Form	Fringing Zone	Aquatic Biota			Additional	
Site No.	**Phys/Chem & Nutrients**	**Bank Stability**	**Riparian**	**Bugs**	**Fish**	**Aquatic weeds**	**Metabolism**	**Feral Impact**
1	+	+	+	+	+	+	+	+
2	+	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+	+
5	+	+	+	+	+	+	+	+
6	+	+	+	+	+	+		+
7	+	+	+	+	+	+		+
8	+	+	+					+
9	+	+	+	+	+	+	+	+
10	+	+	+	+	+	+	+	+
11	+	+	+	+		+		+
12	+	+	+	+	+	+	+	+
13	+	+	+	+		+	+	+
14		+	+					+
15		+	+					+
16		+	+					+
17	+	+	+	+	+	+	+	+
18		+	+					+
19		+	+					+
20	+	+	+	+	+	+	+	+
21	+	+	+	+	+	+	+	+
22	+	+	+					+
23		+	+					+
24	+	+	+	+	+	+	+	+
25	+	+	+		+	+	+	+
26	+	+	+	+	+	+	+	+
27	+	+	+	+		+		+
28	+	+	+	+	+	+	+	+
29	+	+	+	+	+	+	+	+
30	+	+	+	+	+	+	+	+
31	+	+	+	+	+	+	+	+
32	+	+	+	+	+	+	+	+
33	+	+	+	+	+	+	+	+
34	+	+	+	+	+	+		+
35		+	+					
36		+	+					
37					+			

***This table does not include desktop-based assessments of catchment disturbance, hydrology and connectivity. Sites are shown in Figure 3.5 and coordinates in Appendix 13.2.**

grazing and recreational/traditional land-use intensity between June and October 2009. Thirty-seven sites were selected to represent the variety of land-use intensities, where possible, although sites sampled were largely determined by accessibility (see discussion above). Eighteen sites had a complete suite of FARWH indicators and trial measurements assessed. Data for riparian vegetation and physical-form indices were collected at the remaining sites, at which surface water was either absent or non-permanent (Table 3.14; see Appendix 13.2 for coordinates and site description).

3.4 Reference condition

3.4.1 Daly River

Reference condition varies for each FARWH theme and is discussed in each theme chapter.

3.4.2 Fitzroy River

Identification of reference condition

The primary disturbances in the Fitzroy catchment included cattle grazing and altered fire regimes. Both these disturbances are not only hard to quantify (in terms of distribution, intensity and frequency) but are also widespread throughout the catchment. Indeed, only the Fitzroy River and lower reaches of its tributaries (Hann, Adcock and Traine rivers) that run through Mornington and nearby stations (located in the mid-catchment) have management regimes that have included destocking and fire management. Moreover, monitoring of aquatic health using indicators such as macroinvertebrates, fish and riparian vegetation have been largely ad hoc in the Kimberley and no broadscale, coordinated approach using standardised sampling techniques has been undertaken. Consequently the identification of reference sites either within the Fitzroy catchment or in neighbouring catchments is problematic.

Because of these limitations, reference sites were defined as those being ‘minimally disturbed’. Reference sites were only identified within the Fitzroy River catchment as limited information on relevant indicators of river health in nearby catchments did not allow for the identification and application of suitable ‘reference conditions’ outside the Fitzroy catchment with any certainty.

Sites within the catchment were assessed in terms of several criteria based on data collected during the field trials, as well as a review of available literature. Sites needed to meet the following criteria to be selected as reference sites:

(1) Have ‘good-excellent’ riparian condition scores (see Chapter 8, Fringing zone theme)

(2) Have ‘low’ riparian pressure scores (see Chapter 8, Fringing zone theme)

(3) Not be a unique site (e.g. plunge pool below waterfall).

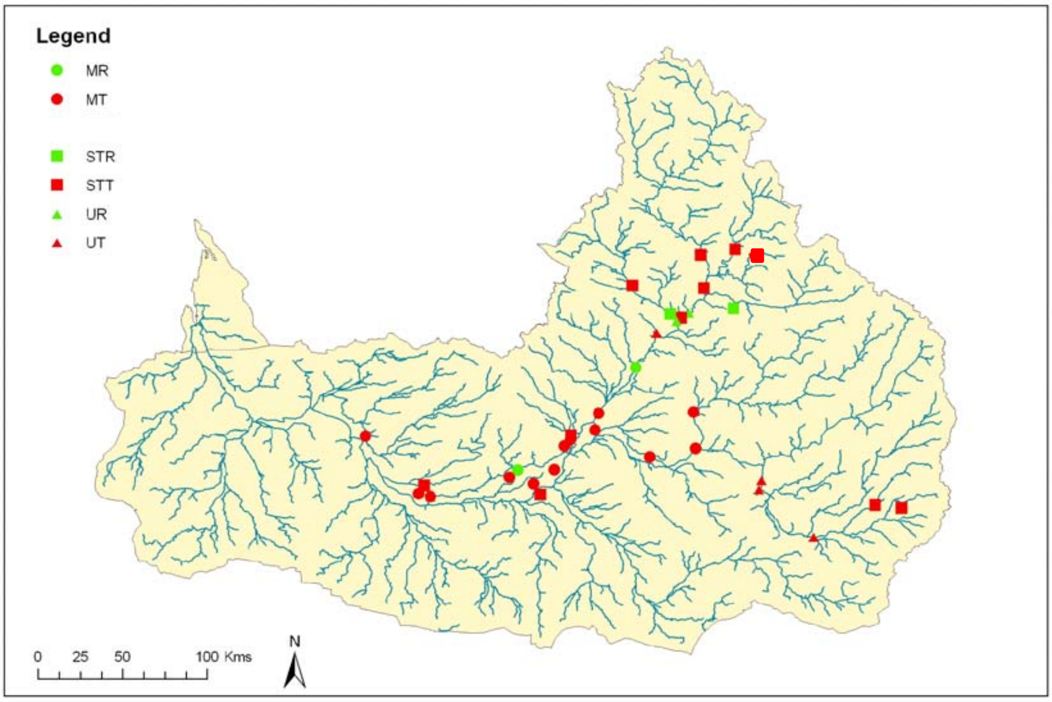
Identification of reference sites

The Fitzroy River catchment is large, covering an area of over 80 106 km^2 (Ruprecht and Rodgers 1998), and comprises reaches with distinct hydrology, geomorphology and habitat (Storey et al. 2001) (see Section 3.1.2). These environmental gradients were expected to influence biophysical indicators of river health, including the distribution and abundance of biodiversity (e.g. fish, macroinvertebrates and riparian vegetation), channel morphology and structural habitat, and water quality. Consequently, it was necessary to investigate whether reference sites were required for different regions within the Fitzroy River catchment.

The distribution and abundance of fish represents the most extensive and available data set relevant to the Fitzroy River field trials of FARWH. This dataset is based on fish surveys undertaken at 70 sites over two years (Morgan et al. 2002, 2004) and provided the only available dataset appropriate to establish whether biogeographic differences could be expected for a range of FARWH indices. Morgan et al. (2004) found a significant difference between the fish assemblages among the lower, mid and upper reaches of the Fitzroy River and its main tributaries (e.g. Margaret and Leopold rivers), which were also significantly different to the smaller, less-permanent tributaries and larger billabongs.

Field trials for FARWH were undertaken at sites that represented the mid and upper reaches of the main channel and major tributaries, and the small tributary groups defined by Morgan et al. (2004). Reference sites were therefore established for each of these broad geographic boundaries, which are referred to in the report as subregions (Figure 3.6).

Figure 3.6: Location of reference sites and test sites sampled in three regions of the Fitzroy River catchment.*



Abbreviations denote sites as: MR, mid-catchment reference site; MT, mid-catchment test site; STT, small-tributary test site; STR, small-tributary reference site; UT, upper-catchment test site; UR, upper-catchment reference site.

The process of assigning reference sites involved:

Step 1—Minimally disturbed sites were identified, based on the TRARC pressure and condition scores measured at each site. Within each subregion, sites with the highest condition and lowest pressure were identified and then refined, using professional judgement to determine which of the sites provided an appropriate reference for each FARWH theme and/or metric (Figure 3.7). The inclusion of both pressure and condition indices was used in this assessment because of limited knowledge of the interaction of both these terms, i.e. it was uncertain whether the 'condition' of sites was consistently related to a variety of pressure indices.

Step 2—As not all metrics were measured at all of the sites, and because the relationship between site condition and pressure remained unclear (Figure 3.7), it was necessary to choose alternate reference sites for some metrics. Pressure and condition scores were combined in a single index, using standardised Euclidean distance, and the distribution of sites was then used to refine the reference site selection and identify additional sites where necessary (Figure 3.8). The highest possible pressure/condition index was used to define these additional reference conditions. The final list of reference sites for each of the FARWH themes and/or metrics in each region (mid, upper and small tributaries) is provided in Table 3.15.

Figure 3.7: Identification of reference sites (red) in each of the mid(•), upper (□) and smaller tributary (▲)reaches of the Fitzroy River.

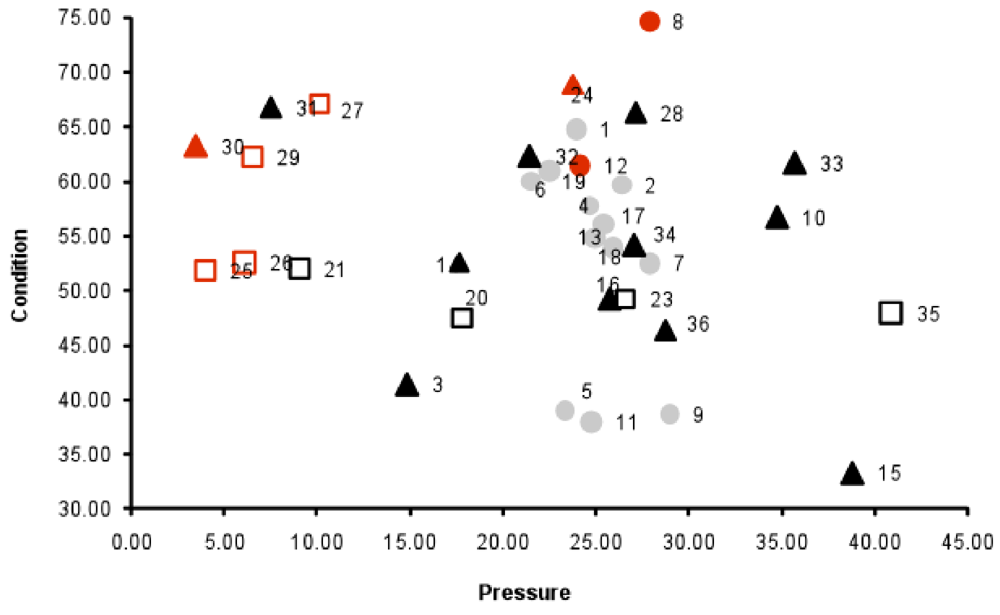


Figure 3.8: Identification of reference sites (red) using the standardised Euclidean distance of pressure and condition scores at each of the 35 sampling sites where TRARC assessments were undertaken.

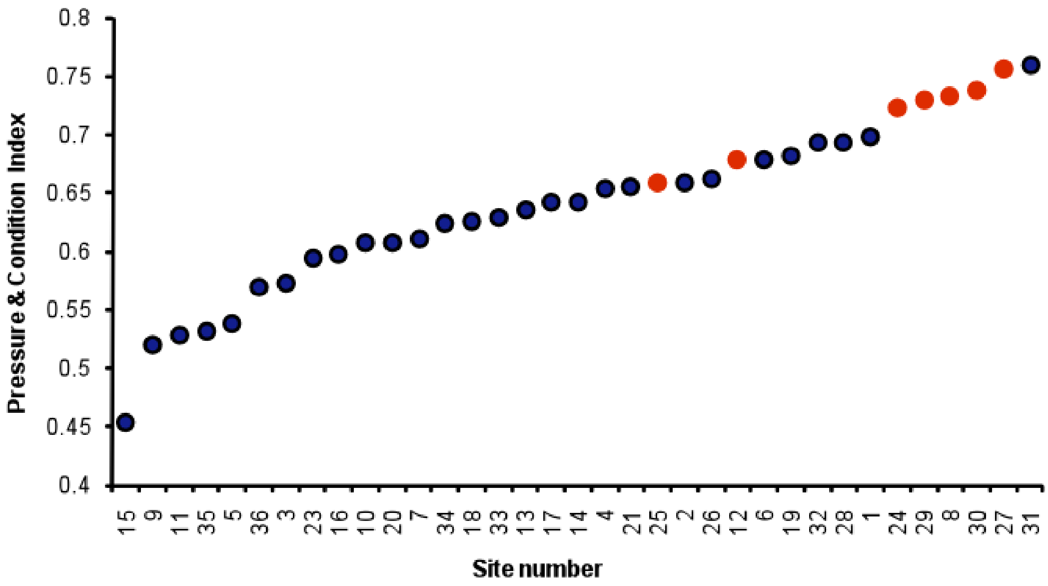


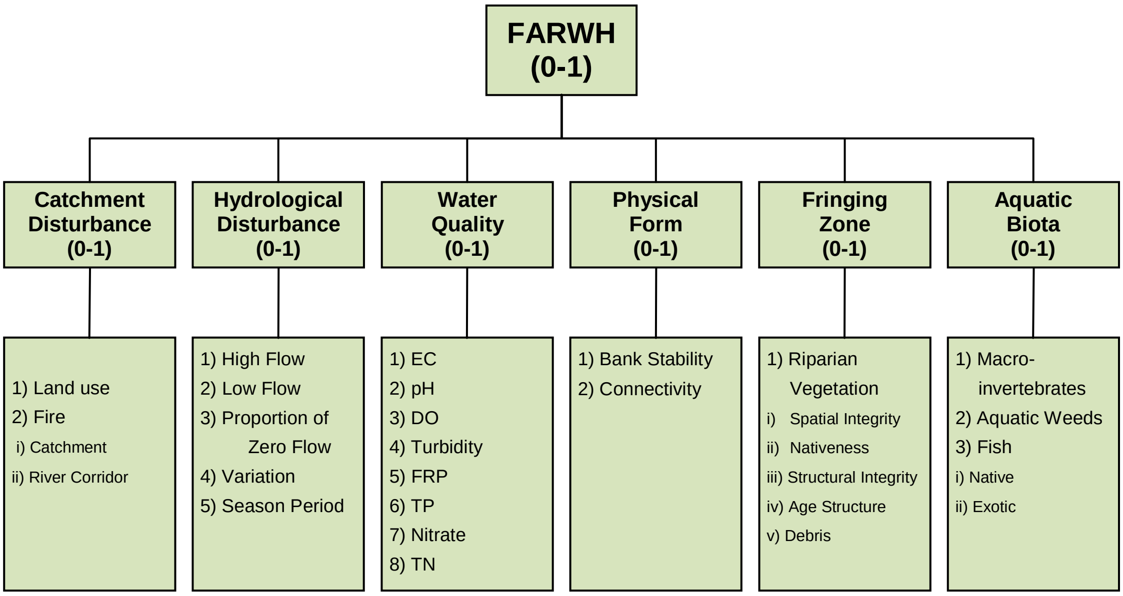
Table 3.15: References sites for FARWH themes within three subregions of the Fitzroy River catchment. Numeric values refer to site no. (Figure 3.6; Appendix 13.2).

Theme	Metric	Upper subregion (Site No.)	Middle subregion (Site No.)	Tributary subregion (Site No.)
Water quality	Water quality	27	8	30
	Nutrients	27	12	30
Aquatic biota	Fish	29	12	30
	Macroinvertebrates	29	8	30
	Dissolved oxygen	25	12	24
Fringing zone & physical form	TRARC	27	8	30

3.5 Indicator selection

For computation of FARWH scores, indicators of river health were grouped into six themes (Figure 3.9). The following chapters provide methods, results and discussion for each theme.

Figure 3.9: Flow diagram of the six FARWH themes and their subindices.



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4 Catchment disturbance theme

4.1 Introduction

The catchment disturbance theme consists of two subindices: 1) land use, and 2) fire. The fire subindex comprised two components: i) burnt catchment and ii) burnt river corridor. Land clearing change was rejected for inclusion as a subindex in the catchment disturbance theme on the basis that it replicated land use (i.e. the land-use score will respond to a change in native vegetation clearing). Also, infrastructure, was rejected due to lack of relevant data (e.g. sealed and unsealed roads) and because similar information was included in one of the land-use classifications. This theme does not address point sources of pollution such as wastewater discharges from mines and wastewater plants. Significant point-source discharges are not known to occur in the two study catchments. The objectives of this chapter are to describe a new method of calculating the fire subindex; and to apply new weightings to land-use classes.

4.2 Methods

4.2.1 Land-use subindex

This was an assessment of catchment-scale, anthropogenic impacts that may influence waterways. It requires dividing the catchment into land-use classes, as defined by the *Australian land use and management classification (ALUM) version 6* (BRS 2007). ALUM groups land uses with similar impacts into six classifications (Table 4.16). Group 2 was divided into two subgroups to better reflect impacts across northern Australia. Each classification was allocated a weighting according to its relative impact on stream health. The weightings used were developed by the Department of Water, Perth (*South-West WA FARWH trial*—Storer et al. 2010), modifying those weightings used in the assessment of river condition (Norris et al. 2001). The fraction of each land-use class was weighted and summed to produce an SWMA land-use subindex score (Equation 4.1).

Table 4.16: Land-use classes with ALUM version 6 classifications and FARWH weightings.

Land-use class	ALUM classification	Weighting
1	Conservation and natural environments	0
2a	Production from relatively natural environments: grazing natural vegetation	0.35
2b	Production from relatively natural environments: production forestry	0.24
3	Production from dryland agriculture and plantations	0.53
4	Production from irrigated agriculture and plantations	0.70
5	Intensive uses	0.68
6	Water	0

Equation 4.1

$$LU = 1 - ((F_1 * w_1) + (F_2 * w_2) + \ldots)$$

where:
LU = ***land-use subindex score (0–1)***
F_1 = ***fraction of land-use class***
w_1 = ***weighting of land-use class.***

4.2.2 Fire subindex

The fire subindex is a new score that was introduced in the FARWH desktop trial (Dixon et al. 2009). Alternative methods to produce the fire subindex have been developed for the Daly River catchment and are presented below. However, computation of scores for the Fitzroy River SWMA uses the original desktop trial method. In consultation with the FARWH steering committee, we recommend that future implementation of the fire subindex in the Fitzroy River and other wet/dry tropical SWMAs use the methods described below for the Daly River.

The fire subindex comprises of two components that are equally weighted (Equation 4.2): i) burnt catchment; and ii) burnt river corridor.

Equation 4.2

$$F = (BC * 0.5) + (BRC * 0.5)$$

where:
F = ***fire subindex score (0-1)***
BC = ***burnt catchment score***
BRC = ***burnt river corridor score.***

Daly River fire subindex

Burnt catchment

This is a measure of the extent and frequency of fire in the SWMA. Fires in the late dry season have greater impacts on stream water quality than fires in the early dry season (Townsend and Douglas 2000). The index only considers fire in the late dry season between August and December and uses weightings based on the annual frequency of fire in the previous five years (Table 4.17). Repeated late dry season burning over several years reduces native vegetation cover and may result in the delivery of higher sediment, nutrient and organic loads to the river network

Raster grids of monthly fire scars from 2005–09 were obtained from NRETAS. For each year, a grid (100 m x 100 m) of the extent of late-season fire was generated using ArcGIS and used to calculate the frequency of fire over a five-year period. The area occupied by each frequency class was expressed as a fraction of the total area. A burnt catchment score was calculated by multiplying the fraction burnt by the frequency weightings (Equation 4.3).

Table 4.17: Weightings for frequency of fire between August–December 2005–09.

No. of years burnt	Weighting
0	0
1	0.2
2	0.4
3	0.6
4	0.8
5	1

Equation 4.3

$$BC = 1 - ((A_1 * w_1) + (A_2 * w_2)\ldots+\ldots(A_5 * w_5))$$

where:
BC = ***burnt catchment score (0–1)***
A = ***fraction of catchment burnt in each frequency class***
w = ***weighting of each frequency class.***

Burnt river corridor

This is a measure of the area burnt by late-season fire within the river corridor weighted by annual frequency of fire within the past 5 years (Table 4.17). The river corridor was defined in ArcGIS, using the Daly stream network (1:250 000) as the area extending 250 m from either side of the river channel. The buffer was then converted to a raster format with 100 m grid cells. The burnt river corridor score was calculated using the same methods as burnt catchment score by applying Equation 4.4.

Equation 4.4

$$BRC = 1 - ((A_1 * w_1) + (A_2 * w_2)\ldots+\ldots(A_5 * w_5))$$

where:
BRC = ***burnt river corridor score (0–1)***
A = ***fraction of area burnt in each frequency class***
w = ***weighting of each frequency class.***

Fitzroy River fire subindex

The fire subindex comprised two components that were equally weighted (Equation 4.5): i) burnt catchment; and ii) burnt river corridor.

Equation 4.5

$$F = (BC * 0.5) + (BRC * 0.5)$$

where:
F = ***fire subindex score for the SWMA (0-1)***
BC = ***burnt catchment score for the SWMA***
BRC = ***burnt river corridor score for the SWMA.***

Burnt catchment (Fitzroy)

This subindex was calculated, using a measure of the catchment area burnt with seasonal weightings applied. Using appropriate fire-scar data for the previous year of sampling, the area burnt within the SWMA was calculated for each month. To reflect seasonal impacts of fire (see above), different weightings were applied depending on the fire month (Table 4.18). A burnt catchment score was calculated by multiplying the fraction of catchment burnt by seasonal weightings (Equation 4.6).

Table 4.18: Weightings for season of fire for previous year.

Season of fire (during previous year)	Weighting
Unburnt	0
January–June	0
July–August	0.5
September–December	1

Equation 4.6

$$BC = 1 - ((A_1 * w_1) + (A_2 * w_2)\ldots+\ldots(A_4 * w_4))$$

where:
BC = ***burnt catchment score (0–1)***
A = ***fraction of catchment burnt during each season***
w = ***weighting of each season.***

Burnt river corridor (Fitzroy)

This is a measure of area burnt within the river corridor and weighted for month of fire (Table 4.18). Using appropriate fire-scar data for the previous year of sampling, area burnt within 250 m of the entire stream network (i.e. 500 m-wide corridor; 1:250 000 drainage map) was calculated for each month. A burnt river corridor score was calculated by multiplying the fraction of corridor burnt by seasonal weightings (Equation 4.7).

Equation 4.7

$$BRC = 1 - ((A_1 * w_1) + (A_2 * w_2)\ldots+\ldots(A_4 * w_4))$$

where:
BRC = ***burnt river corridor score for the SWMA (0–1)***
A = ***fraction of area burnt during each season***
w = ***weighting of each season.***

4.2.3 Integration to the catchment disturbance theme

For the Daly River SWMA, where scores have been aggregated to a stratified zone (developed and undeveloped), an additional integration step was used to compute each subindex and final catchment disturbance theme score. For each subindex (land use and fire), zone scores were weighted by their proportional area of the total SWMA: developed zone = 10 095 km^2 (19%); undeveloped zone = 42 552 km^2 (81%) (Equation 4.8).

Equation 4.8

$$SI = (SI_D * 0.19) + (SI_U * 0.81)$$

where:
SI = ***subindex score for the Daly River SWMA (0–1);***
SI_D = ***subindex score for the Daly River developed zone (0–1); and***
SI_U = ***subindex score for the Daly River undeveloped zone (0–1).***

Integration of land use and fire into the catchment disturbance theme for the SWMA (Fitzroy River) or stratified zone (Daly River) follows

Equation 4.9. Land use is given a higher weighting (80%) than fire (20%) due to the limited knowledge of the impact of fires on aquatic biota and because impacts of land use have a longer term effect and are more likely to vary as development pressures increase across northern Australia.

Equation 4.9

$$CD = (LU * 0.8) + (F * 0.2)$$

where:
CD = ***catchment disturbance theme (0-1)***
LU = ***land-use subindex score***
F = ***fire subindex score.***

4.3 Results

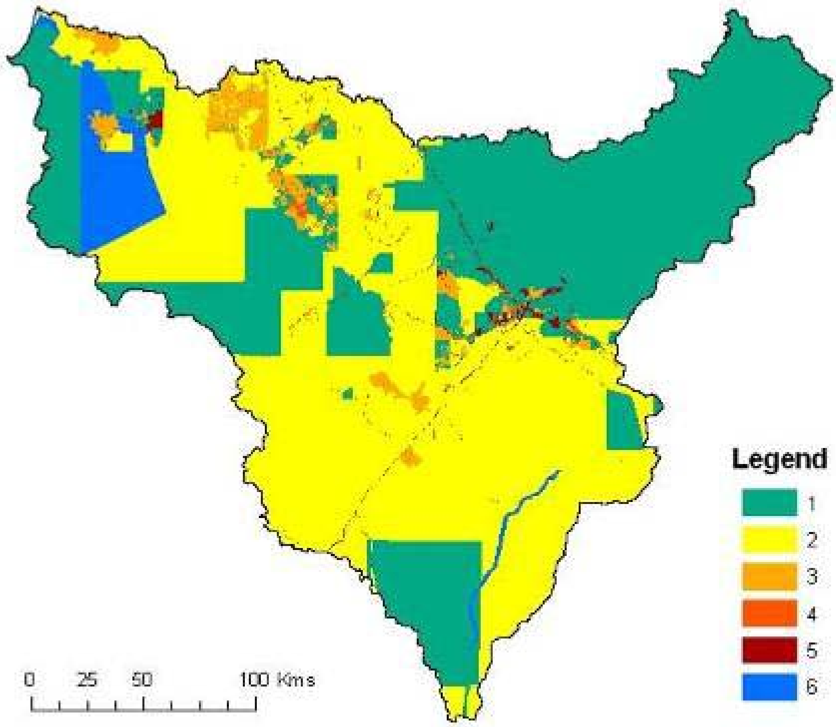
4.3.1 Daly River Catchment

Land use

Data obtained from the revised land-use mapping of the Northern Territory (LUMP08, GDA 1994 MGA Zone 52; Berghout et al. 2008) were used to map land-use classes (Figure 4.9). Weightings were applied to the fraction of each land use class and combined to give a final land-use score of 0.71 and 0.82 for the developed and undeveloped zones of the Daly River catchment. (Land uses are classified using the Australian land use and management classification (ALUM) version 6 (BRS 2007). Land-use classes are listed in Table 4.16.

Table 4.19

Figure 4.9: Land-use classes in the Daly River catchment mapped from revised land-use mapping of the Northern Territory (LUMP08; Berghout *et al.* 2008).*



Land uses are classified using the *Australian land use and management classification (ALUM) version 6* (BRS 2007). Land-use classes are listed in Table 4.16.

Table 4.19: Calculation of land-use subindex for the a) developed and b) undeveloped' zones of the Daly River SWMA, using Equation 4.1. Land-use classes are described in Table 4.16. Final scores are between 0–1, with a higher score implying better condition.

(a) Developed zone

Land-use class	Area (km^2)	Fraction	Weighting	Fraction x weighting
1	2633	0.26	0.00	0.00
2a	5838	0.58	0.35	0.20
2b	0	0.00	0.24	0.00
3	1278	0.13	0.53	0.07
4	101	0.01	0.70	0.01
5	202	0.02	0.68	0.01
6	42	0.00	0.00	0.00
∑	10 095	1.00		0.29
1-∑				**0.71**

(b) Undeveloped zone

Land-use class	Area (km^2)	Fraction	Weighting	Fraction x weighting
1	19 233	0.45	0.00	0.00
2a	20 499	0.48	0.35	0.17
2b	0	0.00	0.24	0.00
3	535	0.01	0.53	0.01
4	6	0.00	0.70	0.00
5	207	0.00	0.68	0.00
6	2073	0.05	0.00	0.00
∑	42 552	1.00		0.18
1-∑				**0.82**

Fire

Fire mapping of the catchment used moderate resolution imaging spectroradiometer (MODIS) fire-scar data for 2005–09 from the NT Bushfires Council (100 x 100 m pixels). Weightings were applied to the frequency of area burnt to give a fire subindex score composed of the burnt catchment score (Table 4.20) and the burnt river corridor score (Table 4.21). The frequency of fire in river corridor is mapped in Figure 4.10. The burnt catchment score and burnt river corridor score were combined (Equation 4.2) to give a fire subindex score of **0.81** and **0.80** for the developed and undeveloped SWMAs of the Daly River catchment.

Table 4.20: Calculation of the burnt catchment score for the a) developed and b) undeveloped zones of the Daly River SWMA, using Equation 4.3*.

(a) Developed zone

No. of years burnt	Area (km^2)	Fraction	Weighting	Fraction x weighting
0	4576	0.45	0.00	0.00
1	3018	0.30	0.20	0.06
2	1419	0.14	0.40	0.06
3	968	0.10	0.60	0.06
4	86	0.01	0.80	0.01
5	27	0.00	1.00	0.00
∑	10 095	1		0.18
1-∑				**0.82**

*** Final scores are between 0–1, with a higher score implying better condition.**

(b) Undeveloped zone

No. of years burnt	Area (km^2)	Fraction	Weighting	Fraction x weighting
0	16 051	0.38	0.00	0.00
1	14 347	0.34	0.20	0.07
2	8542	0.20	0.40	0.08
3	2666	0.06	0.60	0.04
4	880	0.02	0.80	0.02
5	78	0.00	1.00	0.00
∑	42 564	1		0.20
1-∑				**0.80**

Figure 4.10: Fire frequency in 500 m stream corridors in Daly River SWMA. Developed zone of Daly River catchment is shaded.

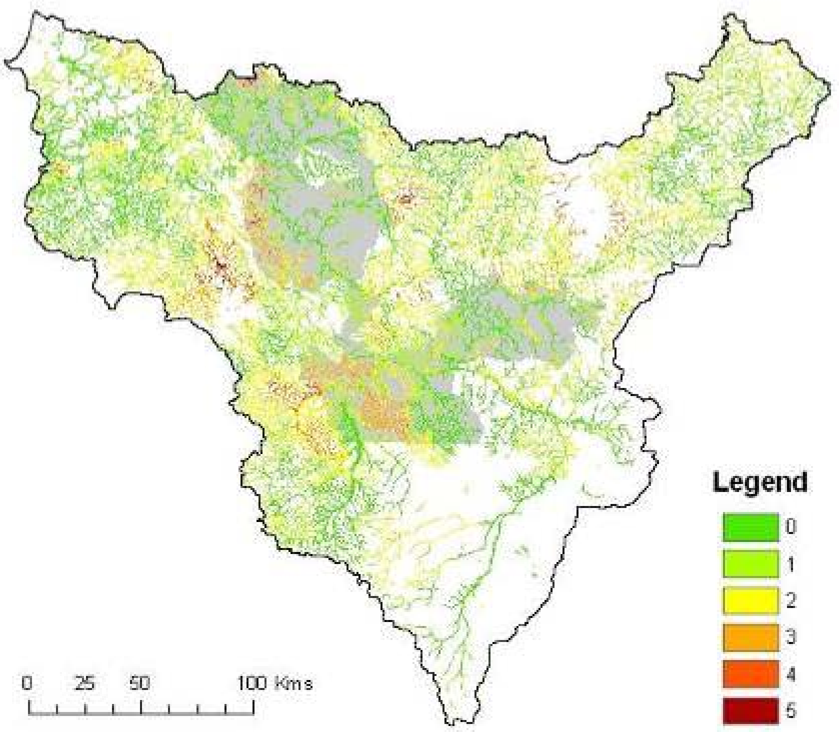


Table 4.21: Calculation of the burnt river corridor score for the a) developed and b) undeveloped zones of the Daly River SWMA, using Equation 4.4. Final scores are between 0–1, with a higher score implying better condition.

(a) Developed zone

No. of years burnt	Area (km^2)	Fraction	Weighting	Fraction x weighting
0	1147	0.41	0	0.00
1	807	0.29	0.2	0.06
2	445	0.16	0.4	0.06
3	328	0.12	0.6	0.07
4	29	0.01	0.8	0.01
5	8	0.00	1	0.00
∑	2764			0.21
1-∑				**0.79**

(b) Undeveloped zone

No. of years burnt	Area (km^2)	Fraction	Weighting	Fraction x weighting
0	3900	0.37	0	0.00
1	3708	0.35	0.2	0.07
2	2016	0.19	0.4	0.08
3	716	0.07	0.6	0.04
4	200	0.02	0.8	0.02
5	18	0.00	1	0.00
∑	10558			0.20
1-∑				**0.80**

4.3.2 Daly River: integration to the catchment disturbance theme

Using Equation 4.8, land use and fire subindex scores were derived for the Daly River SWMA (Table 4.22). Using

Equation 4.9, subindices were integrated to give a final catchment disturbance theme score of **0.73 and 0.82** for the developed and undeveloped zones; and a final score of **0.80** for the of the Daly River SWMA (Table 4.22).

Table 4.22: Integration of subindices to produce a catchment disturbance theme score for the a) developed and b) undeveloped zones of the Daly River SWMA*.

SWMA	Land use (80%)	Fire (20%)	Catchment disturbance theme
Developed zone	0.71	0.81	**0.73**
Undeveloped zone	0.82	0.80	**0.82**
Daly River SWMA	**0.80**	**0.80**	**0.80**

4.4 *** Each zone is weighted for contributing area to give a SWMA subindex score (Equation 4.8) and final theme score (**

Equation 4.9). Scores are between 0–1, with a higher score implying better condition.

4.4.1 Fitzroy River Catchment

Land use

Land-use data obtained from the Department of Agriculture and Food Western Australia (DAFWA) was used to map land-use types based on *ALUM version 5* classifications (BRS 2006). It should be noted that mapping is likely to have been conducted at 1:250 000 resolution across the catchment and may not detect small areas of development. Land- use classes identified in the Fitzroy River catchment were allocated to only two land-use classes. Weightings were applied to the proportion of each land-use class and combined to give a final land-use score of **0.67** (Table 4.23).

Figure 4.11: Land uses for the Fitzroy River catchment classified, using the *Australian land use and management classification (ALUM) version 5 for Western Australia.*

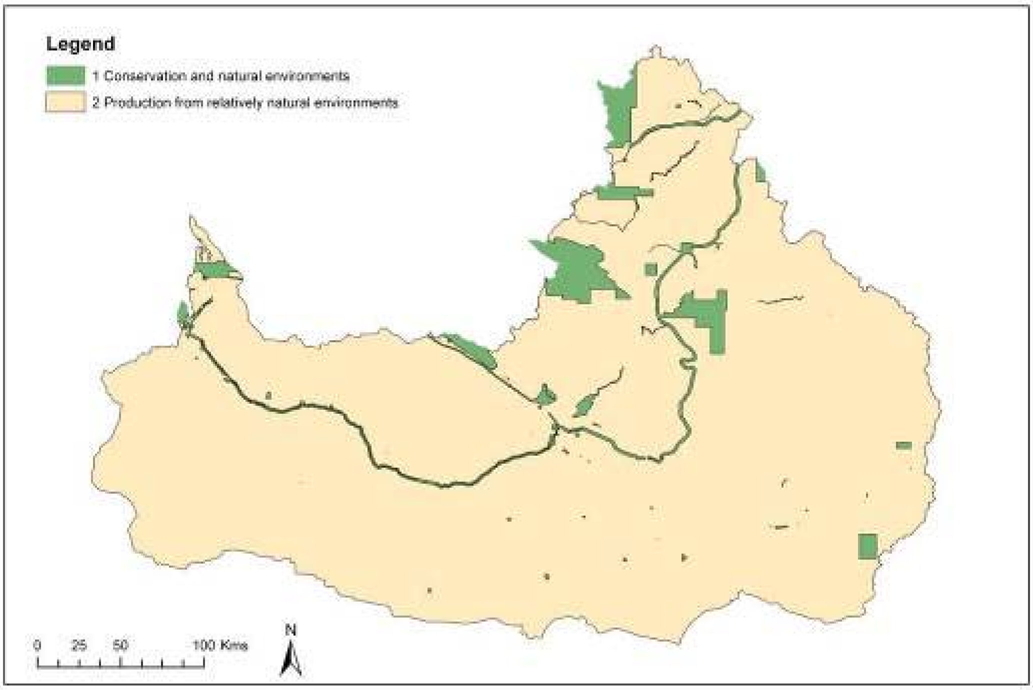


Table 4.23: Calculation of the land-use subindex for the Fitzroy River SWMA using Equation 4.1.*

Land-use class	Area (km^2)	Fraction	Weighting	Fraction x weighting
1	4682	0.06	0.00	0.00
2a	89 371	0.94	0.35	0.33
2b	0	0.00	0.24	0.00
3	0	0.00	0.53	0.00
4	0	0.00	0.70	0.00
5	0	0.00	0.68	0.00
6	0	0.00	0.00	0.00
∑	95 053	1		0.33
1-∑				**0.67**

*** Land-use classes are described in Table 4.16. Final score is between 0–1, with a higher score implying better condition.**

Fitzroy River: fire (burnt catchment)

Fire mapping of the catchment used MODIS fire-scar monthly 2008 data from the *North Australia fires information* web page (Tropical Savannas CRC 2009) (Figure 4.12). Weightings were applied to the proportion of area burnt for each month to give a Burnt Catchment score of **0.83** (Table 4.24).

Figure 4.12: Fire scars identified by MODIS for 2008 in the Fitzroy River catchment.

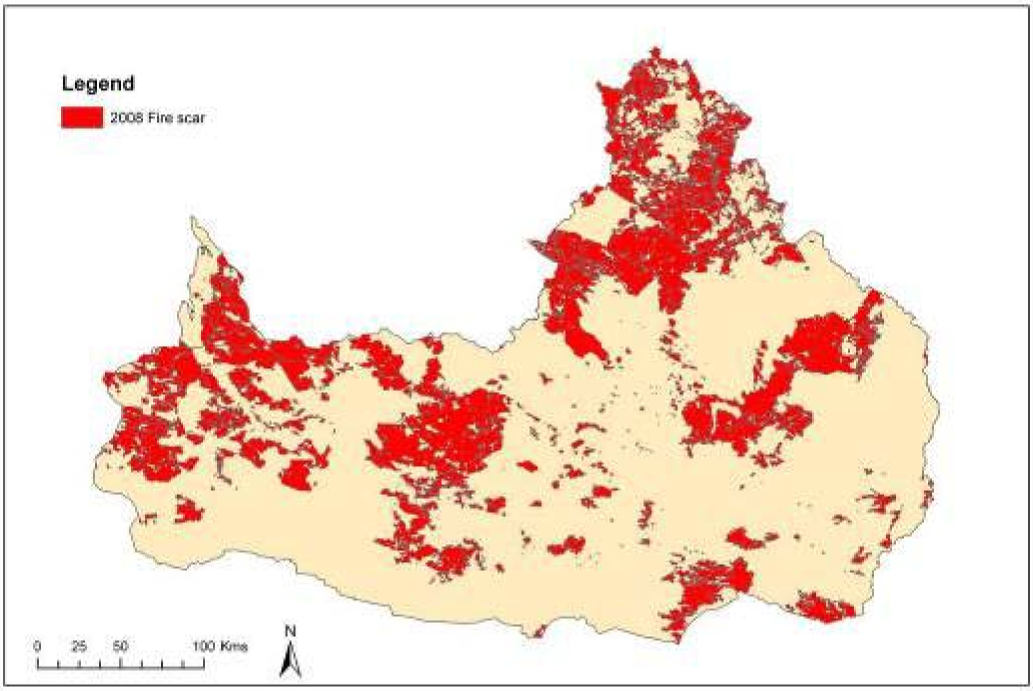


Table 4.24: Calculation of the burnt catchment score in the Fitzroy River SWMA, using Equation 4.6.*.

Month	Area (km^2)	Fraction	Weighting	Fraction x Weighting
No fire	68 500	0.72	0	0
April	3396	0.04	0	0
May	5361	0.06	0	0
June	659	0.01	0	0
July	888	0.01	0.5	0.005
August	1185	0.01	0.5	0.006
September	2844	0.03	1	0.03
October	10 911	0.11	1	0.115
November	1171	0.01	1	0.012
December	138	0.00	1	0.001
∑	95 053	1		0.169
1-∑				**0.83**

* **Final score is between 0–1, with a higher score implying better condition.**

Fitzroy River: fire (burnt river corridor)

The 1:250,000 scale drainage map was used for the Fitzroy River catchment. A 250 m buffer was applied to both sides of all streams, resulting in a combined area of 5908 km^2. Fires were mapped using 2008 MODIS fire-scar data, showing fires by month (Figure 4.13). Weightings were applied to the proportion of corridor burnt for each month to give a burnt river corridor score of **0.87** (Table 4.25).

Figure 4.13: Fire scars identified by MODIS in the 500 m stream corridors of the Fitzroy River catchment.

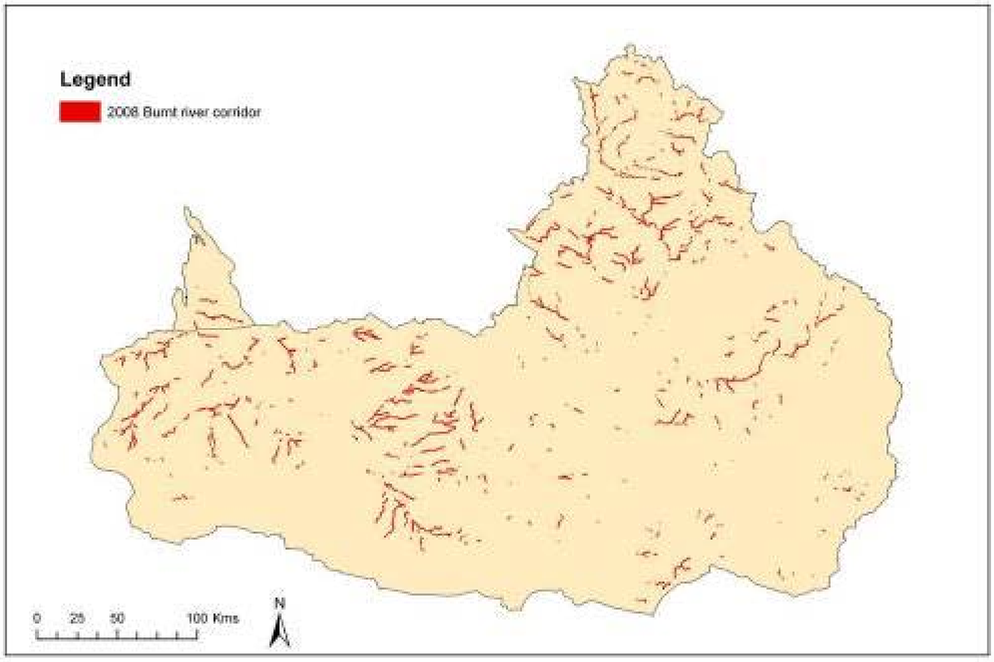


Table 4.25: Calculation of the burnt river corridor score in the Fitzroy River SWMA, using Equation 4.7.*

Month	Area (m^2)	Fraction	Weighting	Fraction x Weighting
No fire	4597	0.778	0	0
March	7	0.001	0	0
April	189	0.032	0	0
May	264	0.045	0	0
June	37	0.006	0	0
July	25	0.004	0.5	0.002
August	46	0.008	0.5	0.004
September	159	0.027	1	0.027
October	509	0.086	1	0.086
November	64	0.011	1	0.011
December	11	0.002	1	0.002
∑	5909	1		0.132
1-∑				**0.87**

***Final score is between 0-1, with a higher score implying better condition.**

4.4.2 Fitzroy River: integration to the catchment disturbance theme

Burnt catchment and burnt river corridor scores were averaged to give a fire subindex score of 0.85. Using
Equation 4.9, Land-use and fire subindices were integrated to give a final catchment disturbance theme score of **0.71** for the Fitzroy River SWMA (Table 4.26).

Table 4.26: Integration of subindices to produce a catchment disturbance theme score for the Fitzroy River SWMA. Scores are between 0–1, with a higher score implying better condition.

SWMA	Land Use (80%)	Fire (20%)	Catchment Disturbance theme
Fitzroy	0.67	0.85	**0.71**

4.5 Discussion

Land use

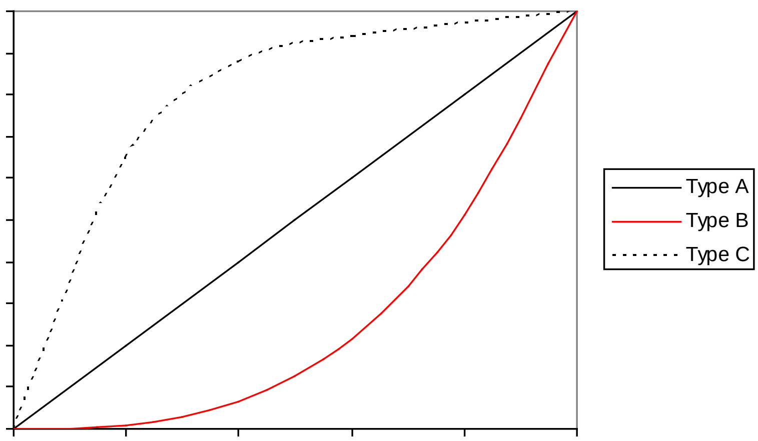
Revised weightings for land-use classes were provided by the WA DoW (South West Western Australia FARWH team—Storer et al. 2011), following a review of the recognised impacts of land use on stream health. We believe these weightings are appropriate for use in the wet/dry tropics and provide an improved comparative method across Australia.

Fire

Although some information is available on the impact of fire on water quality, the response of biota and other water-dependent conditions remains unclear. Given these uncertainties, a low weighting was applied to the fire subindex for integration to the catchment disturbance theme.

Different methods for the calculation of the fire subindex score have been applied in the two SWMAs. While the approach developed in the desktop trial was applied to the Fitzroy SWMA, an alternative method recognising the impact of fire frequency was applied in the Daly River catchment. Fires that burn the same areas in consecutive years, or more than once within a five-year window, are likely to have more impact on river health than periodic burning at longer intervals. While the method applied to the Daly River SWMA is more complex, it is likely to provide a more sensitive approach for assessing the impact of fire on river health. As the ecological response to fire frequency remains unknown, potential weightings for scoring were examined. For example, Figure 4.14 shows three hypothetical relationships between ecological effects and the number fires over a five-year period and provides weightings for each. The influence of these weightings on the burnt river corridor score for the Daly River was then examined The final score was **0.79** with a linear response (Type A), **0.95** when a cubic transformation weighting was used for more frequent fire (Type B), and **0.54** with higher weightings for low fire frequency (Type C). However, there is little empirical basis to the weightings, and in the absence of further evidence a simple linear response (Type A) was used for the fire subindex.

Figure 4.14 Three weightings trialled for late dry season fire frequency over a five-year period: Type A, linear response (preferred method); Type B, cubic response with higher weighting for greater frequency; and Type C, higher weighting for low fire frequency.



Catchment Disturbance Theme

In comparison with earlier desktop trials in the Darwin Harbour and Ord River SWMAs (Table 4.27), the difference in methods should be noted: 1) weightings for some land-use classes were lower in the desktop trial SWMAs and are notably relevant for cattle grazing (Class 2a) in the Ord River SWMA; and 2) the fire subindex in the Daly River SWMA uses weightings for frequency of five over a five-year period, rather than time of fire in a single year.

Table 4.27 Catchment disturbance theme results from this study and the desktop trial of FARWH in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009). Subindices are weighted 80% for land-use and 20% for fire to produce a final score (0–1).

Measure	Daly River: developed zone	Daly River: undeveloped zone	Fitzroy River	Darwin Harbour	Ord River
Land-use subindex	0.71	0.82	0.67	0.88*	0.83*
Fire subindex	0.81	0.80	0.85*	0.85*	0.96*
Catchment Disturbance Theme	**0.73**	**0.82**	**0.71**	**0.87**	**0.85**

***Note: calculation of the fire subindex and weightings for land-use class differ to those recommended in this study.**

In conclusion, the land-use class weightings provided by WA DoW are recommended for use in the wet/dry tropical FARWH. Future application of the fire subindex should follow the five-year frequency method as described for the Daly River SWMA.

4.6 Literature cited

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5 Hydrological disturbance theme

5.1 Introduction

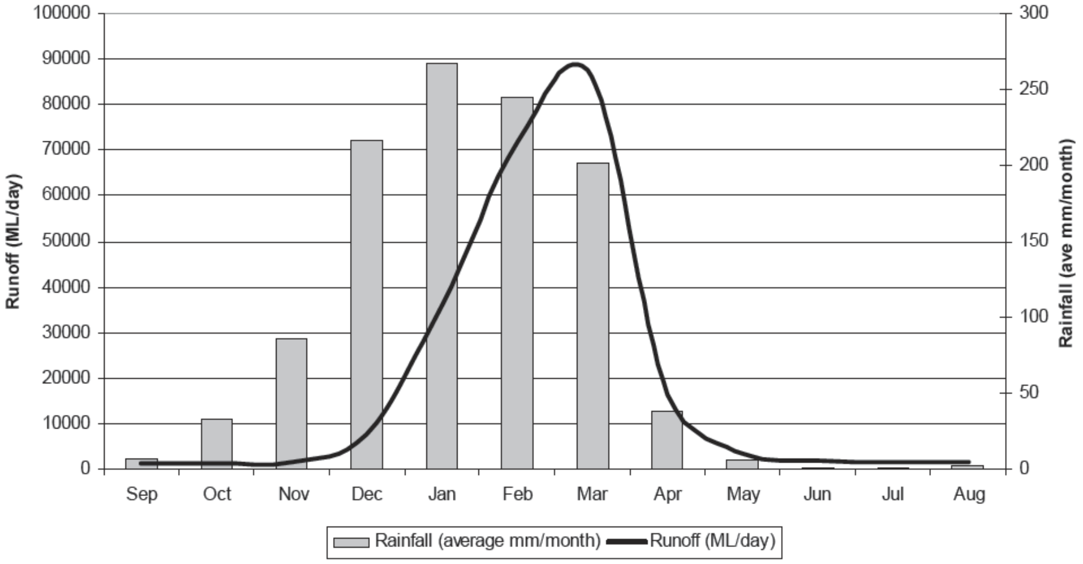
In this chapter the anthropogenic impacts on the hydrology of the Daly and Fitzroy catchments are assessed. These catchments are characterised by low levels of hydrologic disturbance, in contrast to the Ord River and Darwin Harbour catchments in which river flows have been substantially altered by large impoundments and smaller regulation structures (Dixon et al. 2009). The objectives of this chapter are to 1) provide a quantitative assessment of the impact of current and future surface and groundwater extraction on stream flow regime, and 2) provide a qualitative assessment of changes in stream flow.

5.1.1 Rainfall and flow regime

Rainfall is highly seasonal in the wet/dry tropics (Figure 5.1), with greater than 90% falling during the wet season (September to April). The tropical monsoonal trough produces widespread and heavy rainfall between December and March. It is during these months that rainfall can exceed potential evapotranspiration. Rainfall is negligible during the dry season (May to August). During the transition between the dry and wet seasons (September to November) isolated, high-intensity storm events can occur. Highest mean annual rainfall occurs along the coast, and decreases with distance inland. Conversely, interannual variability increases away from the coast. Interannual variability is high (CSIRO 2009a); while wet and dry seasons occur each year, there is considerable variability in wet season runoff volumes. To capture a single wet season, the water year in the wet/dry tropics covers the period from September to August of the following year.

Strong seasonality in rainfall results in predictable river flow patterns. Early wet season flow events, called first flushes, occur following intensive storms. High flood flows then occur during the wet season from surface runoff and subsurface flow (Cook et al. 1998). Connectivity of the river and the groundwater determines whether river flows persist throughout the dry season or rivers cease to flow. The Daly River is an example of a perennially flowing river (Figure 5.1) resulting from connection to high-yielding groundwater aquifers. The Fitzroy River provides an example of a river that ceases to flow during the dry season. However, connection with local groundwater aquifers maintains a chain of large, permanent pools. The majority of streams in the wet/dry tropics are seasonally flowing; they do not flow during the dry season (Pusey et al. 2009).

Figure 5.1: Monthly average rainfall and runoff for Daly River catchment.*



***Rainfall recorded at Katherine Aviation Museum 1942–2008 (BOM 2009); runoff recorded at Mt Nancar 1968–2008 (NRETAS 2009a.**

5.1.2 Anthropogenic impacts on flow regime in the wet/dry tropics

The savanna landscape that dominates the wet/dry tropics is characterised by a continuous layer of grasses and a discontinuous layer of trees and shrubs. This creates a patchy landscape finely tuned to water availability (Khomo and Rogers 2009). Anthropogenic activities can disrupt the fine balance in vegetation cover across tropical savanna landscapes, resulting in increased runoff (Ludwig et al. 2005).

Land use in the savanna landscape is dominated by cattle grazing. The rate of clearing of native vegetation for agriculture and improved pasture is increasing and, in localised areas, urban development is rapidly expanding. Initial reviews of anthropogenic impacts on Australia's tropical savanna support the belief that they can no longer be considered in a natural, pre-European state (Pusey et al. 2009).

Cattle grazing

Rangeland health across northern Australia has recently been reported by the Australian Collaborative Rangeland Information System (ACRIS 2008a,b,c). Many areas have reported an increase in woody vegetation and an increase in late dry season fires. From this assessment, only three regions in Queensland were reported to be sustainably grazed (ACRIS 2008a). In many of the regions assessed, pastoral management increased stocking rates during seasons of good rain but did not de-stock in poorer seasons, indicating marginal sustainability (ACRIS 2008a) and increased susceptibility to erosion.

Cattle grazing can cause groundcover loss due to preferential grazing of areas with more palatable fodder and concentration of cattle around cattle yards, watering points and holding paddocks. Grazing can also increase soil compaction (Greenwood and MacKenzie 2001) and cause alteration of soil biological and hydrological properties (Roth 2004). However, it is difficult to assess the impact of these changes on stream-flow regimes because of difficulties in quantifying effects both at a local and catchment-wide scale. Nonetheless, previous studies have shown that de-vegetation of hillslopes can significantly increase runoff by as much as six-to-nine fold, compared with naturally vegetated areas (Bartley et al. 2006). This study, and others (Timble and Mendell 1995) suggested that runoff from hillslopes was likely to increase when de-vegetation exceeded approximately 60% (Bartley et al. 2006). The study by Timble and Mendell (1995) specifically described changes in runoff associated with de-vegetation by cattle. As a precautionary approach, it appears that maintaining at least 40% ground will reduce the risk of hydrologic impact.

Much of the research into the impact of grazing on hydrology, however, has been undertaken in temperate regions. In contrast to the results described above, sediment modelling by Dilshad (2007) in the Daly River catchment found a similar average rate of sediment loss from areas of grazed native vegetation and conservation areas without productive cattle grazing. This suggests, at the catchment scale, there may be limited impact of cattle grazing on hydrology in the wet/dry tropics. Unfortunately, at the catchment scale it is difficult to measure the percentage of ground cover and, moreover, the suitability of applying these thresholds to tropical savanna systems remains largely uncertain

Tree clearing

Initial studies conducted in savanna landscapes in Queensland suggested that removing native vegetation and establishing improved pasture had little or no effect on water balance, runoff or soil loss as long as ground cover was maintained (Prebble and Stirk 1988). However, more recent work in the Daly River catchment suggested evapotranspiration was greatly reduced in recently de-vegetated areas relative to areas with native savanna (Wilson et al. 2006). This can result in greater (~1 order of magnitude) aquifer recharge in de-vegetated areas compared with naturally vegetated landscapes and was attributed to the replacement of native, deep-rooted, perennial vegetation (e.g. eucalypts*)* with shallow-rooted, annual grass species (Wilson et al. 2006). The loss of deep-rooted perennial vegetation is a common cause of increased groundwater levels across Australia. The sites used in the study described above were located above the Oolloo dolostone aquifer, a high-yielding aquifer with high hydraulic connectivity to the Daly River. The major aquifer recharge pathways are macropore and soil matrix flow. It was speculated land clearing would result in greater discharge of groundwater to the Daly River (Wilson et al. 2006).

In another study, clearing of brigalow scrub for agriculture generated an increase in catchment runoff of 40% in the Queensland Comet River catchment (Siriwardena et al. 2006). The increase in catchment runoff was accompanied by a 50% increase in baseflow, suggesting greater drainage to the groundwater system. The proportion of cease-to-flow conditions was reduced from 72% of the year to 58% with catchment clearing. This supports the contention that enhanced recharge to the groundwater system contributed to increased base flows during the dry season.

Another potential impact to savanna hydrology is introduced flora and the indirect effect it has on catchment vegetation by replacing native flora and altering fire regime (e.g. gamba grass).

Fire regime

The frequency and intensity of fires in the wet/dry tropics have increased since European settlement. Fires occur more frequently later in the dry season, when intensities are generally greatest. The current management approach is to reduce fuel loads with early dry season burns, with some land managers also applying wet season burns. The burning of savanna woodland in the lowlands of Kakadu National Park (KNP) late in the dry season (September) reduced catchment canopy cover and groundcover, as well as riparian vegetation, but did not have a detectable impact on water yield (Townsend and Douglas 2000). The relatively low slopes of the KNP study catchments (<1%), and the rapid regrowth of grasses after rainfall (which have high evapotranspiration rates), could have mitigated any impact on catchment yield. While the build-up of fuel poses a threat to high-intensity fires, even after 10 years of no burning, an early dry season fire can result in no significant impact on runoff volume when the fire intensity is low (Townsend and Douglas 2004).

Contrastingly, late dry season fires can affect stream-flow regime by increasing overland surface water connectivity with the stream from episodic storm events during the dry/wet or 'build-up' season (Townsend and Douglas 2000; Townsend et al. 2004). These runoff events have high concentrations of sediment, nutrients, iron and manganese that have reportedly caused fish kills (Townsend et al. 1992) but contribute a negligible volume to annual runoff.

Urban development

Analysis of hydrographic data in the Darwin Harbour catchment has provided an assessment of the impact of urban development on hydrology. Because of the replacement of native vegetation with impervious surfaces and drains, urban development has approximately doubled the volume of runoff compared to an undisturbed landscape (Skinner et al. 2009). Runoff coefficients in urbanised areas of Darwin (~0.5) were found to be similar to other urban areas of Australia that typically range between 0.5–0.8 (Barry et al. 2004).

A secondary impact on flow regime for urbanised catchments is an increase in flow during the dry season. This is due to excess garden irrigation by households and councils, and the emptying of domestic swimming pools into the stormwater system.

Surface water storage and extraction

The majority of river systems across northern Australia do not have regulated flow. The greatest diversion occurs within the Ord River catchment for irrigation supply and hydroelectricity generation. The disturbance to natural flow regimes due to impoundment of water has been assessed for the Ord River and Darwin River by Dixon et al. (2009).

The CSIRO's Northern Australia Sustainable Yields Project found there was limited opportunity for future impoundment of surface water across the wet/dry tropics. Large storages are required to exceed evaporative demand and account for the high spatial variability of annual rainfall in headwater areas where most suitable dam sites exist (CSIRO 2009b).

Groundwater storage and extraction

Watertables of aquifers across the wet/dry tropics respond to seasonal rainfall. They can recharge by several metres over the wet season, or to capacity, before discharging gradually during the dry season. These systems can be an important source of water for anthropogenic use, and are important in maintaining ecological communities in the savanna landscape (Braithwaite and Muller 1997). Sustainable levels of groundwater extraction are generally not known, yet management of these systems is critical to ensure groundwater-dependent ecosystems are maintained, particularly during the dry season when ecological and human demands for groundwater overlap and ecological/hydrological stress is at its highest.

Significant groundwater extraction is occurring within the Tindall limestone around Katherine, and Oolloo dolostone in the Daly River catchment. Modelling and monitoring networks are being used to develop water allocation plans in these areas (Yin Foo 2004; URS 2008). Water allocation plans for these aquifers are either in place or being developed.

5.2 Methods

For the Daly River SWMA, unlike the other five FARWH themes, the hydrological disturbance theme was not calculated for each of the two strata (developed and undeveloped zones); rather, it was applied to the entire SWMA (due to staffing availability at the time of this study).

5.2.1 Quantitative evaluation of hydrologic disturbance

The Hydrologic Disturbance Index is a measure of how anthropogenic impacts have changed river flow regimes. These impacts are primarily river and groundwater extraction in the Daly and Fitzroy catchments. To provide a sound assessment, concurrent modelled datasets of the flow regime are required to ensure changes are due to anthropogenic disturbance and not the climatic regime. A modelled dataset is available for groundwater extraction in the Katherine region, and its impact on Katherine River flow downstream of Katherine township.

Anthropogenic impact on hydrology in the wet/dry tropics has not previously been quantified. To fill the knowledge gap, and more specifically the impact of land clearing on river flow regime, a TRaCK research project has begun (Hutley et al. 2008).

For The FARWH trials, the FSR procedure has been applied to assess the impact of land-use change on river flows. .The FSR procedure was developed to provide an objective ranking of threats to river health based on the level of anthropogenic water extractions and consumptive use (SKM 2005). The procedure was developed in Victoria for the Department of Sustainability and Environment to assess flow stress across the state. The FARWH trial is the first time the procedure has been trialled in the wet/dry tropics.

The FSR procedure compares five flow indices between unimpacted conditions (predisturbance) and current (disturbed) hydrologic conditions (SKM 2005). The five indices are:

- high flow: the change in the magnitude of high flows
- low flow: the change in the magnitude of low flows
- proportion of zero flow: comparison of proportion of zero flows
- seasonality: comparison of the difference in the magnitude between high and low flows,
- variability: comparison of the change timing of the maximum and minimum flows.

The FSR procedure provides high confidence in results when applied to temporally continuous datasets of at least 15-years duration. Two datasets are required for the FSR and are generated by rainfall runoff modelling on a monthly timestep:

- predevelopment (‘natural’): time series from (observed data from pre-impact period) + (post-impact observed data, suitably adjusted to represent conditions, assuming the impact is not present during the post-impact period)
- post-development (‘current’): time series from (pre-impact observed data suitably adjusted to represent conditions as if impact present over pre-impact period) + (post-

impact observed data).

The FSR procedure provides an indication of the level of disturbance to each flow index by applying a value between 0 and 1, where zero is a complete change from predevelopment flow and 1 is no change from predevelopment flow. The average for the five flow indices is then calculated to provide the score for each reach.

With input from Rory Nathan (SKM Melbourne), the calculation for the FSR was slightly modified to suit the wet/dry tropics. These modifications were:

- Measurement year. Adjusted from calendar year to 'water year' (September to August). Use of this timestep captures the whole wet season in a single hydrological year and is easier to explain to stakeholder groups
- Calculation of FSR indices. Ecological importance of each flow index was assessed for the wet/dry tropics. Seasonality and variability were assessed over the water year, while high flow was assessed over the wet season only and low flow and proportion of zero flow were assessed over the dry season only (Table 5.1)
- All indices equally weighted. In the Victorian case study it was found appropriate to use double weighting for seasonality (see discussion below).

Table 5.1: FSR indices and most applicable season in the wet/dry tropics.

Index	Season	Months	Justification
High flow	Wet season	Dec.–April	High flow for all river systems in the wet/dry tropics occurs during the wet season. FSR results for Ord River indicate using an annual timestep dampens the modelled impact of damming on high flows.
Low flow	Dry season	May–Nov.	Low flow for all river systems in the wet/dry tropics occurs during the dry season. FSR results for the Ord River indicate the same score is calculated for annual or dry season calculations.
Proportion of zero flow	Dry season	May–Nov.	The greatest impact of damming and water extraction on the proportion of zero flow occurs during the dry season.
Variation	Water year	Sept.–Aug.	FSR results indicate changes in flow variation due to damming occurring throughout the water year.
Seasonality	Water year	Sept.–Aug.	This index has been applied to the water year to capture the impact on the wet and dry seasons.

Application of the FSR in Victoria (SKM 2005) applied a double weighting to the Seasonality Index to accentuate the impact of large dams. Large dams in Victoria have had a considerable ecological impact on the seasonal flows of river systems (e.g. Goulburn River, FSR seasonality score, 0.58 (SKM 2005, p. 112). Table 5.2 provides an assessment of double-weighting seasonality in the wet/dry tropics, which produced marginal changes in the final score of 0.04 for the Darwin and Ord river systems. A double-weighted Seasonality Index had a small influence to the overall Hydrological Disturbance Index (HDI) score for both of the trial catchments. As such, double-weighting of the Seasonality Index was not applied to these FARWH FSR trials. Until further knowledge is gained on the ecological impact of the five FSR indices, they were all weighted equally.

Table 5.2: Sensitivity of double-weighting seasonal period for the Darwin and Ord Rivers*.

Catch-ment	Wet season high flow	Dry season low flow	Propor-tion of zero flow	Variat-ion	Season-ality	Avg.	Double-weighted season-ality	Ch-ange
	Dec.–Apr.	May–Nov.	May–Nov.	Water yr	Water yr			
Darwin River	0.48	0.74	0.99	0.55	0.43	0.64	0.60	0.04
Ord River	0.42	0	0.4	0.52	0.61	0.39	0.43	0.04

***A score of 0 implies greatest impact, and a score of 1 implies no impact.**

The disadvantage of the FSR procedure is it can only be applied to streams where there is gauged or modelled pre- and post-development data. In the wet/dry tropics there is limited modelled data available. The method for applying the FSR to changes in flow regime due to change in land use is currently being developed by SKM. For this assessment, the FSR has been applied to change-in-flow regime due to land use by expert opinion. A user guide for calculation of the FSR flow indices is provided in Appendix 13.3.

5.2.2 Qualitative assessment of hydrologic disturbance

The majority of rivers and reaches in the Daly and Fitzroy catchments have low hydrologic disturbance and do not have modelled flows. Consequently, a qualitative assessment of land-use impacts on hydrologic disturbance was required. Land-use classes shown in Table 5.3 have been selected for the Daly and Fitzroy catchments. Weightings have been developed based on literature review and expert opinion. These weightings are indicative only.

Table 5.3: Qualitative assessment of hydrological impact of change in land use.

Land-use class	Likely hydrologic impact at reach scale (assumptions)	FSR indices	Impact	FARWH score
Grazing with natural vegetation	Tropical savanna canopy and grassland system intact. Likely to be reduced groundcover in isolated areas—cattle yards, water points, preferred pasture, cattle tracks. Catchments with greater than 30% bare ground likely to have higher runoff volume (Bartley et al. 2006). Impact on flow regime: Greater wet season high flow. A weighting of 0.98 has been applied to indicate a deviation away from natural conditions. Frequent high-intensity fires are common in Daly and Fitzroy catchments. Townsend and Douglas (2000) found fire regime had negligible impact on catchment yield, though an increase in episodic runoff events at beginning of wet season was recorded. Not reflected in FSR. Estimates of water consumption for cattle indicate cattle may consume 0.5–1% of catchment yield during the dry season. Cattle rely significantly on natural water sources in Daly and Fitzroy catchment. Impact on flow regime: dry season low flow. A weighting of 0.98 has been applied to indicate a deviation away from natural conditions. Knowledge gap: impact of compaction and reduced ground cover from grazing on savannas. No data available assessing vegetation cover on pastoral leases (ACRIS 2008a, b, c).	Wet season high flow	Yes	0.98
		Dry season low flow	Yes	0.98
		Dry season prop. zero flow	No	1
		Annual variation	No	1
		Annual seasonality	No	1
		Average		0.99

Land-use class	Likely hydrologic impact at reach scale (assumptions)	FSR indices	Impact	FARWH score
Land cleared of native vegetation	Tropical savanna canopy and grassland system removed. Groundcover likely to be intact, especially during crop growth. Reduced rooting depth. Reduced evapotranspiration. Increased recharge via diffuse and preferential flow pathways (Wilson et al. 2006; Hutley et al. 2008). Increased recharge to the Daly River (Wilson et al. 2006) during the wet and dry seasons. Impact on flow regime: wet season high flow, dry season low flow and proportion of zero flow. Knowledge gap: impact of groundwater extraction for irrigation in areas cleared of native vegetation (CSIRO 2009a)	Wet season high flow	Yes	0.97
		Dry season low flow	Yes	0.95
		Dry season prop. zero flow	Yes	0.94
		Annual variation	No	1
		Annual seasonality	No	1
		Average		0.97
Urbanis-ation	Vegetation removed, increased impervious surface. Approximate doubling of runoff during wet season (Skinner et al. 2009). Impact on flow regime: greater wet season high flow. Increased dry season flows due to excessive domestic irrigation. Impact on flow regime: dry season low flow, proportion of zero flow, annual variation and annual seasonality.	Wet season high flow	Yes	0.5
		Dry season low flow	Yes	0.9
		Dry season prop zero flow	Yes	0.8
		Annual variation	Yes	0.9
		Annual seasonality	Yes	0.9
		Average		0.8

5.2.3 Aggregation of quantitative and qualitative assessments

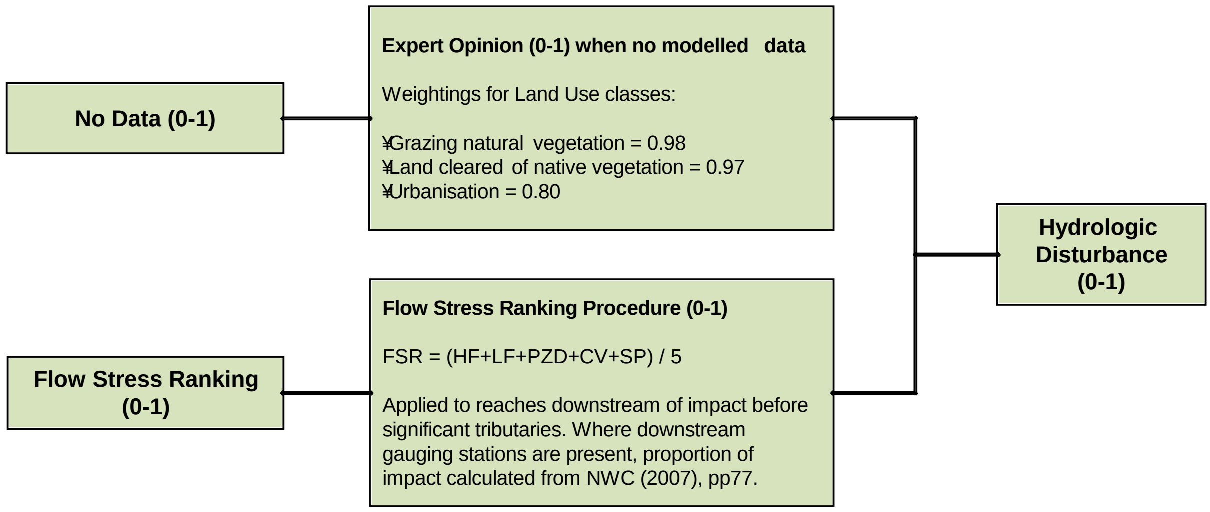
Aggregation of the five FSR indices (high flow, low flow, proportion of zero flow, variation and seasonal period) was completed at the reach scale by calculating the arithmetic mean (Figure 5.2). Aggregation of the individual reach-index scores across each catchment was completed by calculating length-weighted average of all reach scores. For reaches with no available data, expert rules were applied to give scores to grazing, cleared land and urbanisation (Figure 5.3).

Figure 5.2: Aggregation of the FSR indices at the reach scale.

Description (SKM 2005)	Equation	Flow Stress Ranking (FSR) Index	Weight
***HF8.3* = Range-standardised low flow index based on the 8.3% exceedance flow** *Q8. 3c* = Current 8.3% exceedance flow (ML) *Q8.3n* = Unimpacted 8.3% exceedance flow (ML) *Pile(Q8.3c)* = Proportion of years that the current 8.3rd percentile flow is exceeded by the annual 8.3rd percentile unimpacted flow *Pile(Q8.3u)* = Proportion of years that the unimpacted 8.3rd percentile flow is exceeded by the annual 8.3rd percentile unimpacted flow Repeated for 16.7% exceedance flow and averaged		**High Flow (0-1)**	**20%**
***LF91.7* = Range-standardised low flow index based on the 91.7% exceedance flow** *Q91. 7c* = Current 91.7% exceedance flow (ML) *Q91.7u* = Unimpacted 91.7% exceedance flow (ML) *Pile(Q91.7*c) = Proportion of years that the current 91.7th percentile flow is exceeded by the annual 91.7th percentile unimpacted flow *Pile(Q91.7u*) = Proportion of years that the unimpacted 91.7th percentile flow is exceeded by the annual 91.7th percentile unimpacted flow Repeated for 83.3% exceedance flow and averaged		**Low Flow (0-1)**	**20%**
***PZ* = Proportion of zero flow index** *PZu* = Proportion of zero flow over the whole record under unimpacted conditions *PZc* = Proportion of zero flow over the whole record under unimpacted conditions	$PZD = 1 - 2 \times \left[\max\left(PZu, PZ_c\right) - \min\left(PZ_u, PZ_c\right)\right]$	**Proportion of Zero Flow (0-1)**	**20%**
CV = Index of monthly variability CVc = Current monthly coefficient of variation CVu = Unimpacted monthly coefficient of variation	$CV = \frac{CV_c}{CV_u}$	**Variation (0-1)**	**20%**
***SP* = Comparison of frequency distribution seasonal period index** *PHCi* = The percentage of years the *i*th month has the peak annual flow under current conditions (%). *PHUi* = The percentage of years the *i*th month has the peak annual flow under unimpacted conditions (%). *PLCi* = The percentage of years the *i*th month has the minimum annual flow under current conditions (%). *PLRi* = The percentage of years the *i*th month has the minimum annual flow under reference conditions (%).	$SP = \frac{1}{200}\left\{\sum_{i=1}\left[MIN\left(PHC_i, PHU_i\right)\right] + \sum_{i=1}\left[MIN\left(PLC_i, PLU_i\right)\right]\right\}$	**Seasonal Period (0-1)**	**20%**

Hydrologic Disturbance (0-1)

Figure 5.3: Aggregation of the reach FSR and expert rule scores to the SWMA scale. Reach index aggregated to basin index by calculating length-weighted average of all reach scores (NWC)



2007).

5.3 Results

5.3.1 Daly River catchment: hydrologic impacts

Cattle grazing

Cattle grazing on tropical savanna grassland is the dominant land use in the Daly catchment. Cattle rely significantly on natural water points as a source of water (ACRIS 2008b; ACRIS 2008c), though farm dams are present.

Land clearing

Between 1977 and 2008, the total amount of land cleared of native vegetation, based on satellite imagery, was 5.32% (NRETAS unpublished data). The majority (two-thirds) of this clearing has occurred on pastoral leases for improved pasture or fodder cropping to increase carrying capacity of stock (Hosking 2002).

Fire

The impact of how frequent high-intensity fire increases on the likelihood of episodic flow events early in the wet season is not known and has not been included in the hydrologic disturbance theme. The area burnt by fire, however, is included in the CDI.

Surface water extraction

Impoundment is not significant in the Daly River catchment. The largest dam in the catchment is Copperfield Creek Dam (capacity approximately 4000 ML) to supply the township of Pine Creek. During the wet season water is pumped to the dam, located in the headwaters of Copperfield Creek, from downstream and has a minor impact on the streams-flow regime.

Donkey Camp Pool storage, located on the Katherine River, supplies 80% of town water (NRETAS 2009b). A surface water extraction licence of 4500 ML exists, with approximately 2700 ML extracted per year for the Katherine town water supply. This is less than 1% of total annual runoff for the Katherine River at Knotts Crossing, below the Donkey Camp Pool. However, approximately 98% of the Katherine River runoff occurs within the wet season (December to April). Therefore the impact of extraction from surface waters may have a pronounced impact on flow regime during the dry season. This will be assessed for the Katherine River system in this report.

Ground water extraction

Significant groundwater extraction occurs in the Daly River catchment for riparian, public or agricultural water supply. Approximately 60 GL is extracted each year from the Daly River catchment for use as irrigation for agricultural crops such as peanuts, mangoes, lucerne, vegetables and other tropical fruits (Tickell 2009). Approximately 900 ML of groundwater is extracted as public water supply for Katherine (NRETAS 2009b). The estimated storage of the Daly Basin aquifers is 350 000 GL, and volume of recharge 1000 GL/annum (Tickell 2009). Completed studies suggest up to 100 GL may be available for resource use from the aquifer system. The Daly Basin is the common term used to describe the geological basin which contains the Tindall–Oolloo aquifer system.

Surface and groundwater extraction in the catchment are considered low (Table 5.4). The 80:20 rule is in effect for environmental water allocation (*Australian Water Resource Audit* 2005); 80% for the environment and 20% for consumption. During 2004–05, the environmental share of total flow in the Daly River was 95% of inflows or 6 742 800 ML (*Australian water resource audit* 2005).

The URS groundwater model for the Katherine River has a number of limitations. It does not include aquifer recharge because of the macropore flow, clearing of native vegetation and discharge from the third major aquifer in the system, the Cretaceous sandstone aquifer. Hutley et al. (2008) are applying surface and groundwater modelling to quantify the impact of clearing of savanna vegetation on aquifer recharge and discharge to the Daly River.

Table 5.4: Estimated extraction from the Daly River catchment ([1]*Australian water resource audit* 2005).

	Daly River catchment	
	Volume (ML)	% of total extraction
Groundwater extraction		
Public water supply	1085	16
Irrigation	1200	17
Surface water extraction		
Donkey Camp Pool	2700	39
Irrigation or other uses	1858	27
Total extraction[1]	643	% total extraction
Sustainable annual water yield[1]	1 415 988	0
Annual mean dry season (May–Oct.) water yield	283 197	2

5.3.2 Daly River catchment: quantitative assessment

Groundwater extraction

The impact of three groundwater extraction regimes for the Katherine region have been modelled by URS (URS 2008; Table 5.5). The scenarios assessed were:

- **Historical groundwater scenario.** Current groundwater extraction rates. Estimated from documented extraction from bores for the water year 2005–06. Assumed Oolloo aquifer had little development before 2008, therefore no extraction from this aquifer is included in the scenario.
- **Current groundwater scenario.** Full entitlements for 2008 used in both Tindall and Oolloo aquifers in the Katherine region.
- **Future allocation scenario.** Current and expected future entitlements in the Tindall and Oolloo aquifers in the Katherine region.

Table 5.5: Annual extraction rates for modelled scenarios (Tindall and Oolloo Katherine aquifers) (URS 2008).

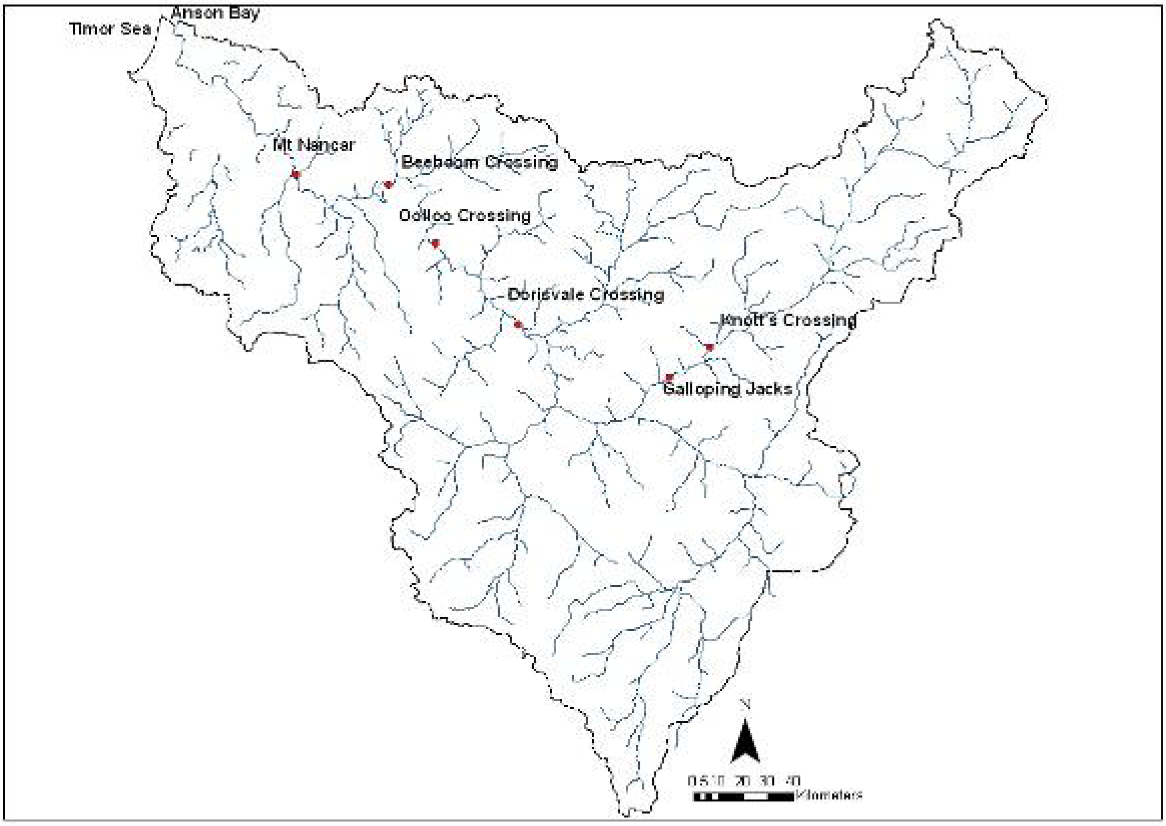
ML/yr	Historic	Current	Future
Tindall	1200	27 900	35 800
Oolloo	0	16 800	43 800
Total	1200	44 700	79 600

This modelled data was suitable to apply the FSR to the Daly River at Mount Nancar, Beeboom Crossing, Oolloo Crossing and Dorisvale Crossing and the Katherine River at

Galloping Jacks and Knotts Crossing (Figure 5.4).

The historical groundwater extraction scenario is based on the current level of groundwater extraction during the water year 2007–08. Application of the FSR indicates that the impact of historical extraction on stream flow in the Daly and Katherine rivers is minimal (Table 5.6; Figures 5.5, 5.6). Lower scores for dry season flows may be due to the imprecision of the modelling. Values calculated using the FSR procedure have a range of 0 to 1, where 1 indicates no change from the natural flow regime, while 0 indicates complete change from the natural flow regime.

Figure 5.4: Locations of modelling of pre- and post-development of groundwater extraction in the Daly River catchment.



With the calculations conducted in the Daly a deviation of 0.05 from 1 (i.e. 0.95) is not necessarily considered indicative of a change from natural-flow regime as it could be due to the imprecision of calculations and modelled data. This is based on the FSR scores shown in Table 5.6, which lists sites downstream from the impact along the Katherine River. For some subindices, the FSR scores fluctuate or decrease, despite increased distance from the impact reach. For example, in Table 5.6 an FSR score of **0.96** was determined for variation for the Daly River site at Mount Nancar, despite it being the most distant from the potential impact on Katherine River flow, and there being higher scores further upstream closer to the impact. The best explanation for this is the FSR model outputs, for this exercise, have an uncertainty of approximately 0.05.

Table 5.6: Results for Daly and Katherine Rivers*

Gauging site	Wet season high flow	Dry season low flow	Prop. of zero flow	Variation	Seasonality	HDI
Season	**Oct.– April**	**May–Nov.**	**May–Nov.**	**Water year**	**Water year**	**Average**
Katherine River at Knotts Crossing	1.00	0.99	1.00	1.00	0.99	0.99
Katherine River at Galloping Jacks	1.00	0.96	1.00	1.00	0.99	0.99
Daly River at Dorisvale	1.00	0.96	0.99	1.00	0.98	0.99
Daly River at Oolloo Crossing	0.98	0.95	0.99	1.00	0.97	0.98
Daly River at Beeboom	1.00	0.98	0.99	1.00	0.96	0.99
Daly River at Mt Nancar	0.99	1.00	0.99	1.00	0.96	0.99

* **Modelled flow data generated from 1900 to 2007 by URS (2008). Historical groundwater extraction (current level). Values of 0.95 to 1 indicate no change from natural flow regime.**

The current groundwater extraction scenario is based on the full use of current groundwater extraction entitlements, approximately 44 700 ML per year. Application of the FSR indicates that current extraction will have a greater impact on stream flow in the Daly and Katherine rivers than the historical scenario (Table 5.7, Figures 5.5, 5.6). The greatest change from natural-flow regimes occurs for the Dry Season Low Flow Index for all sites modelled. The least change from natural-flow regime occurs for wet season, high flow and variation indices. The greatest change occurs in the Katherine River at Galloping Jacks. There is a significant reduction in dry season flows reflected in the dry season low flow and proportion of zero flow indices (Table 5.7, Figures 5.5, 5.6). Modelled data indicates the river will stop flowing in some years. A slight change to the Seasonality Index is also recorded due to delay in wet season flow (Figure 5.7). The end result is an HDI score of **0.66**, indicating disturbance to stream flow at Galloping Jacks. Least impacted sites were at Mount Nancar and Beeboom Crossing.

Table 5.7: Results for Daly and Katherine rivers.*

Gauging site	Wet season high flow	Dry season low flow	Prop. of zero flow	Variation	Seasonality	HDI
Season	**Oct.–April**	**May–Sept.**	**May–Sept.**	**Water year**	**Water year**	**Avg.**
Katherine River at Knotts Crossing	1.00	**0.54**	0.91	1.00	**0.96**	**0.88**
Katherine River at Galloping Jacks	0.99	**0.00**	**0.43**	0.98	**0.91**	**0.66**
Daly River at Dorisvale	1.00	**0.30**	**0.83**	0.99	0.95	**0.81**
Daly River at Oolloo Crossing	0.98	**0.50**	**0.89**	0.99	0.97	**0.87**
Daly River at Beeboom	1.00	**0.67**	0.96	0.99	0.98	**0.92**
Daly River at Mt Nancar	0.99	**0.68**	0.97	0.99	0.97	**0.92**

***Modelled flow data generated from 1900 to 2007 by URS (2008). Current groundwater extraction (full entitlement). Value of 0.95 to 1 indicates no change from natural-flow regime. Impact scores in bold type.**

Figure 5.5: Average monthly flow during the dry season for the Katherine River at Galloping Jacks (1900–2007: URS 2008)

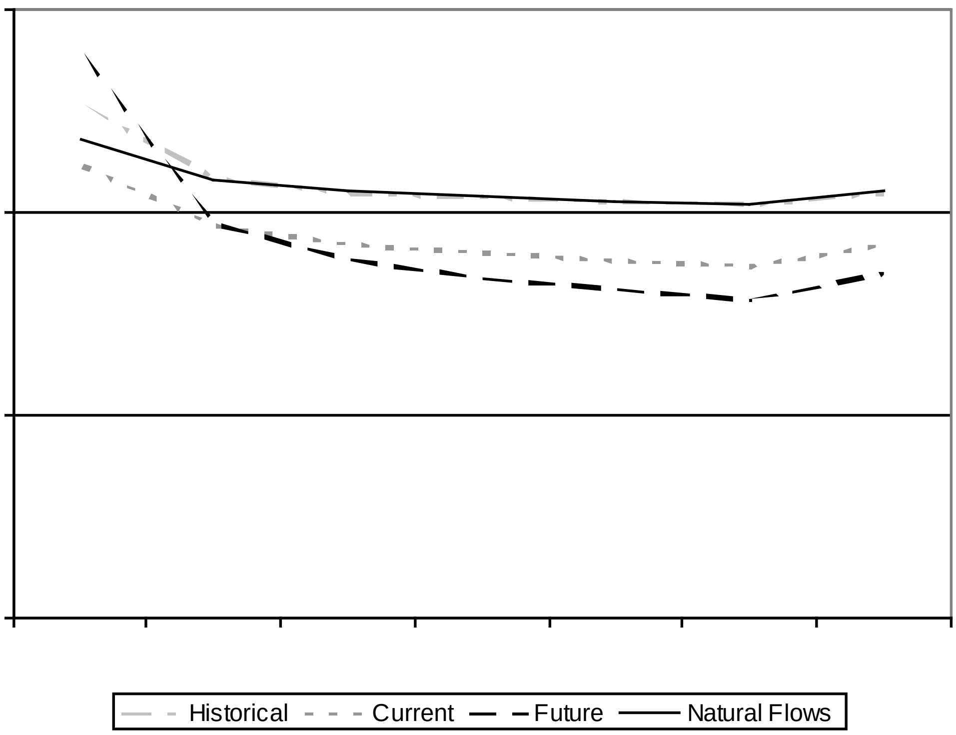
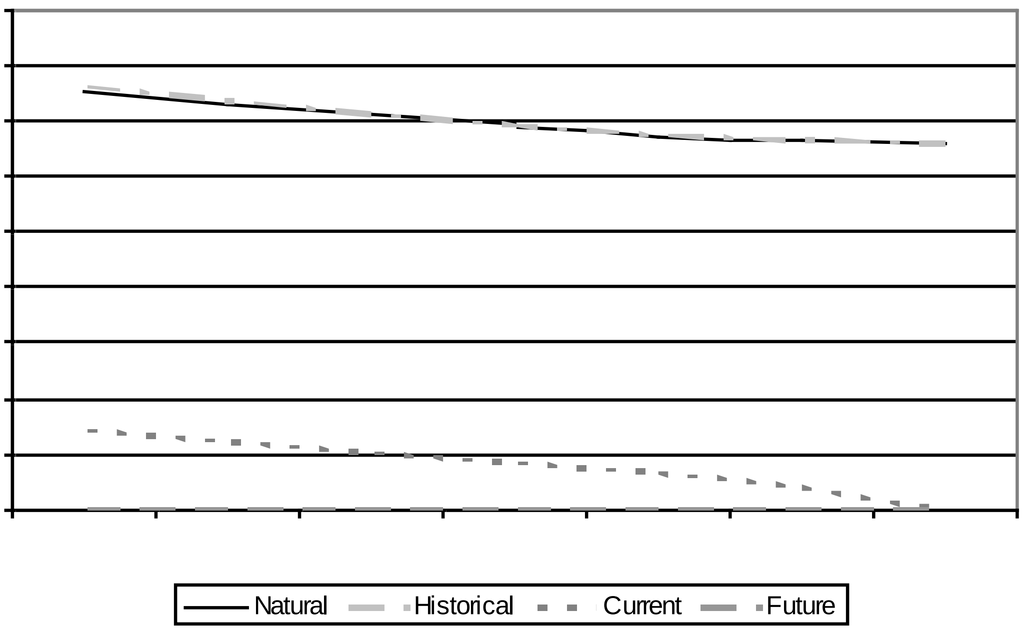


Figure 5.6: Minimum monthlyy flow during the dry season for the Katherine River at Galloping Jacks (1900–2007: URS 2008).



The future groundwater extraction scenario is based on the full use of current groundwater extraction entitlements and estimated future entitlements, approximately 79 600 ML per year. Application of the FSR indicates that future extraction will have a greater impact on stream flow in the Daly and Katherine rivers than the current extraction scenario (Table 5.8; Figures 5.6, 5.7). The greatest change from the natural-flow regime occurs for the Dry Season Low Flow Index for all sites modelled. The Proportion of Zero Flow Index is also impacted for all sites. Least change from natural-flow regimes occurs for the Wet Season High Flow and Variation indices.

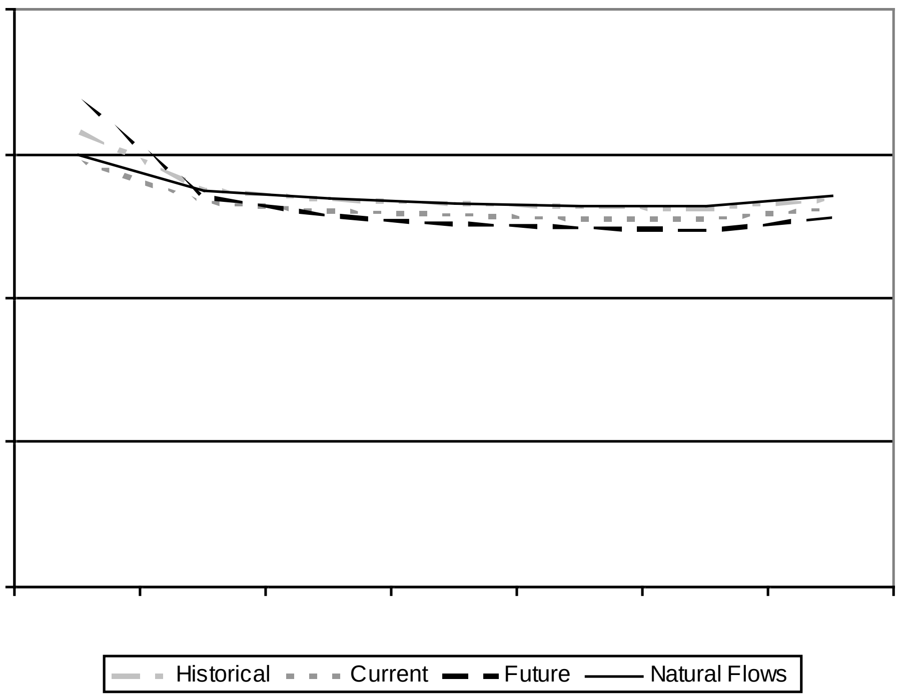
Table 5.8: Results for Daly and Katherine Rivers.*

Gauging site	Wet season high flow	Dry season low flow	Prop. of zero flow	Variation	Season-ality	HDI
Season	**Oct.–April**	**May–Sept.**	**May–Sept.**	**Water year**	**Water year**	**Average**
Katherine River at Knotts Crossing	1.00	**0.41**	**0.69**	0.99	0.95	**0.81**
Katherine River at Galloping Jacks	0.99	**0.00**	**0.00**	0.96	**0.85**	**0.56**
Daly River @ Dorisvale	1.00	**0.10**	**0.19**	0.98	**0.94**	**0.64**
Daly River at Oolloo Crossing	1.00	**0.21**	**0.44**	0.98	**0.93**	**0.71**
Daly River at Beeboom	1.00	**0.45**	**0.70**	0.98	0.96	**0.82**
Daly River @ Mt Nancar	1.00	**0.46**	**0.75**	0.99	0.96	**0.83**

***Modelled flow data generated from 1900 to 2007 by URS (2008). Future groundwater etraction. Impact scores in bold type. Values of 0.95 to 1 indicate no change from natural-flow regime.**

The greatest change occurs in the Katherine River at Galloping Jacks, downstream of groundwater input from the Tindall aquifer. There is a significant reduction in dry season flows reflected in the Dry Season Low Flow and Proportion of Zero Flow indices. In some years the Katherine River would stop flowing. A slight change to the Seasonality Index is also recorded due to delay in the wet season flow. The end result is an HDI score of **0.56**, indicating a moderate disturbance to stream flow. The Daly River at Dorisvale also shows a significant disturbance to the flow regime for this scenario due to impacts on Dry Season Low Flow and Proportion of Zero Flow indices (Figure 5.7). The least impacted sites are at Mount Nancar and Beeboom Crossing (downstream sites) and Katherine River at Knotts Crossing (upstream site).

Figure 5.7: Average monthly flow for the Daly River at Dorisvale (1900–2007: URS 2008)



Groundwater and surface water extraction

To provide an estimate of the impact of surface water extraction from Donkey Camp Pool, monthly extraction volumes for 2007 were provided by NT Power and Water. Surface water extraction licences for agriculture also exist for the Katherine and Daly rivers, though these have not been included in this analysis. Monthly extractions (ML/month) from Donkey Camp Pool were subtracted from the historical modelled flows for the Katherine River at Knotts Crossing and Galloping Jacks, both located downstream from Donkey Camp Pool.

The historical (surface and groundwater extraction) flow regime was compared to the natural flow regime using the FSR procedure. Results indicate surface water extraction for public water supply does affect the flow regime of the Katherine River (Table 5.9, Figure 5.8). The impact is greatest at Knotts Crossing. Changes in dry season low flow and proportion of zero flow indices were recorded for both sites. The seasonality index is also affected for Knotts Crossing. There is little impact for the downstream sites in the Daly River.

Table 5.9: Historical groundwater extraction from Katherine region and surface water extraction from Donkey Camp Pool and their impact on flow regime in the Katherine River. Value of 0.95 to 1 indicates no change from natural flow regime.

Gauging site	Wet season high flow	Dry season low flow	Prop. of zero flow	Variation	Seasonality	HDI
Season	**Oct.–April**	**May–Nov.**	**May–Nov.**	**Water year**	**Water year**	**Avg.**
Groundwater extraction only						
Katherine River at Galloping Jacks	1.00	0.96	1.00	1.00	0.99	0.99
Katherine River at Knotts Crossing	1.00	0.99	1.00	1.00	0.99	0.99
Groundwater extraction and public surface water extraction (from Donkey Camp Pool)						
Katherine River at Galloping Jacks	0.97	**0.69**	**0.94**	0.98	0.94	**0.84**
Katherine River at Knotts Crossing	0.99	**0.57**	**0.87**	0.98	**0.88**	**0.78**

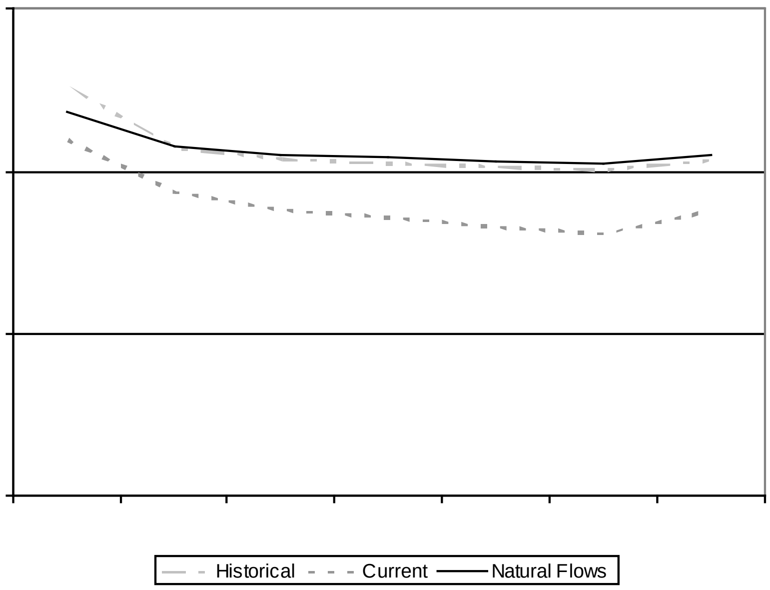
The current annual licence allocation for surface water extraction at Donkey Camp Pool is 4500 ML. This figure was partitioned for a 12-month period using the extraction data provided by NT Power and Water for 2007. Estimated monthly extractions for full use of the current surface water extraction licence were subtracted from the current modelled scenario (URS 2008). The current (full use of current public surface and groundwater extraction licences) flow regime was compared to the natural flow regime using the FSR procedure. The impact of surface water extraction is less clear due to the impact of groundwater extraction on the Katherine River at Galloping Jacks (Table 5.10). The impact of surface water extraction is significant at both sites for dry season low flow and proportion of zero flow indices (Table 5.10). The seasonality index is again slightly impacted.

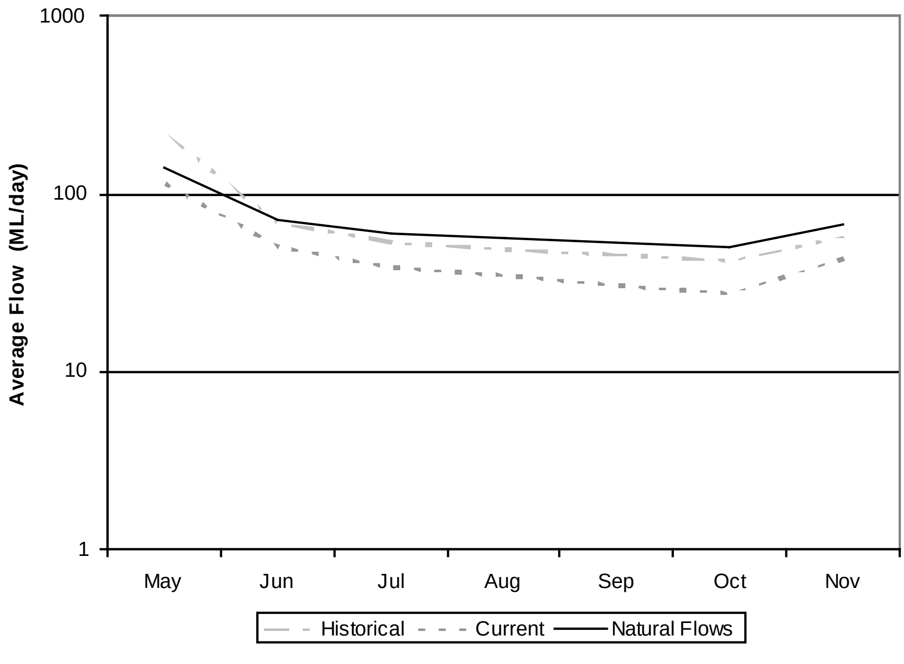
Table 5.10: Full extraction of current groundwater licences from Katherine region and surface water licence from Donkey Camp Pool and their impact on flow regime in the Katherine River.*

Gauging site	Wet season high flow	Dry season low flow	Prop. of zero flow	Variation	Seasonality	HDI
Season	**Oct.–April**	**May Nov.**	**May–Nov.**	**Water year**	**Water year**	**Avg.**
Groundwater extraction only						
Katherine River at Galloping Jacks	0.99	**0.00**	**0.43**	0.98	**0.91**	**0.66**
Katherine River at Knotts Crossing	1.00	**0.54**	0.91	1.00	0.96	**0.88**
Current licence allocation for Surface (from Donkey Camp Pool) and Groundwater Extraction						
Katherine River at Galloping Jacks	0.99	**0.00**	**0.00**	0.97	0.94	**0.38**
Katherine River at Knotts Crossing	0.99	**0.25**	**0.34**	0.99	**0.90**	**0.53**

***Values of 0.95 to 1 indicates no change from natural flow regime.**

Figure 5.8: Surface and groundwater xxtraction and impact on dry season flow regime for Katherine River at Galloping Jacks (top figure) and Knotts Crossing (bottom figure).





To complete the application of the FSR procedure, surface and groundwater extraction scenarios were applied to the Daly River. As expected, the current level of surface water extraction from Donkey Camp Pool had little impact on the average FSR score, with minor impacts on dry season low fow index (Table 5.11). However, application of full surface and groundwater extraction licences provided an impact greater than groundwater extraction alone. The most impact is again on the dry season low flow and on proportion of zero flow indices.

Table 5.11: Historical and current licence groundwater extraction from Katherine region and surface water extraction from Donkey Camp Pool and impact on flow regime in the Daly River.*

Gauging site	Wet season high flow	Dry season low flow	Dry season prop. zero flow	Seas-onality	Variat-ion	Avg.
Season	Oct.–April	May–Nov.	May–Nov.	Water year	Water year	
Historical groundwater extraction and public surface water extraction (Donkey Camp Pool for 2006)						
Daly River at Mt Nancar	0.99	0.94	0.99	0.97	0.98	0.98
Daly River at Beeboom	0.99	0.92	0.99	0.98	0.98	0.97
Daly River at Oolloo Crossing	0.98	0.91	0.98	0.97	0.98	0.95
Daly River at Dorisvale	1.00	0.91	0.96	0.93	0.97	0.96
Extraction of full current licence allocation for surface (Donkey Camp Pool) and groundwater extraction						
Daly River at Mt Nancar	1.00	0.62	0.85	0.97	1.00	0.89
Daly River at Beeboom	1.00	0.62	0.81	0.98	0.99	0.88
Daly River at Oolloo Crossing	0.99	0.44	0.64	0.97	0.99	0.81
Daly River at Dorisvale	1.00	0.21	0.44	0.93	0.99	0.72

*** Value of 0.97 to 1 indicates no change from natural flow regime.**

5.3.3 Daly River catchment: qualitative assessment

The majority (94%) of (NLWRA) reaches in the Daly Catchment are outside the FSR assessment. Each of these reaches was assigned to a hydrological class based on available land-use data (*ALUM*, BRS 2007). Hydrological classes are:

- grazing with natural vegetation (81% of reaches). This includes pastoral stations, Aboriginal and conservation land. Literature review was unable to justify separation of these land uses
- cleared land (13% of reaches)
- land cleared of savanna vegetation for improved pasture or cropping
- urbanisation (<0.01%)
- Katherine township—the only significant urban land use in the catchment (<0.01%).

A qualitative assessment of each class has been developed and is summarised in Table 5.3.

5.3.4 Daly River catchment: aggregation

Scores were aggregated to give a final hydrological disturbance theme score of **0.96** for the Daly River SWMA. This indicates, at present levels of development, that there is minimal impact at the catchment scale. Grazing with natural vegetation was found to have the greatest influence on the hydrologic disturbance score due to dominance of the catchment and a weighting of **0.98** (Table 5.12).

Table 5.12: Aggregation of hydrologic disturbance scores for each reach in the Daly River catchment.

Hydrological class	No. of reaches	Total length (km)	Proportion of total reach network	Reach score	FARWH score
Grazing with natural vegetation	278	3766	0.79	0.98	0.77
Cleared land	60	632	0.13	0.97	0.12
Urbanisation	2	19	0.00	0.80	0.00
FSR	26	358	0.08	0.91	0.07
Total	**366**	**4775**	**1.0**		**0.96**

The FSR score aggregation was based on the current groundwater use and surface water use in the catchment (Table 5.13). The FARWH method recommends scores for a particular reach can be directly applied to downstream reaches until confluence with a tributary downstream (NWC 2007). In the case of the Daly River, only tributaries with dry season flow were considered significant. The FSR score only applies to 7% of reaches in the catchment. Because of the small proportion of stream network suitable for the FSR assessment, future scenarios would have had little bearing on the catchment result; for example, if the current and future scenarios had been used the overall catchment score would be **0.97**.

Table 5.13: Aggregation of FSR scores for the Katherine and Daly rivers.

FSR site	FSR score: historical extraction (surface and groundwater)	Length of stream network	Prop. of total stream network (4775 km) by FSR score	FSR reach network weighted score
Katherine River at Galloping Jacks	0.84	36.73	0.008	0.086
Katherine River at Knotts Crossing	0.78	68.27	0.014	0.149
Daly River at Dorisvale	0.96	118.61	0.025	0.318
Daly River at Oolloo Crossing	0.95	31.87	0.007	0.085
Daly River at Beeboom	0.96	71.79	0.015	0.193
Daly River at Mt Nancar	0.97	30.83	0.006	0.084
Total (sum.)		**358.01**	**0.075**	**0.914**

At the current level of development in the Daly River catchment there was no measurable disturbance to flow regime from groundwater extraction based on URS-modelled data. There was an impact on dry season low flows and proportion of zero flow indices in the Katherine River due to surface water extraction for public water supply. This localised result is not reflected in the overall catchment score, and highlights the ‘dilution effect’ of applying the FARWH to large catchments where there may be significant impact in only a small proportion of the catchment. This analysis is based on qualitative and quantitative procedures. Future scenarios of groundwater extraction do have impacts on flow regime, especially for the Katherine River.

5.3.5 Fitzroy River catchment: hydrologic impacts

Cattle grazing

Approximately 40% of the pastoral leases in the Fitzroy River catchment are owned by Aboriginal corporations and have been de-stocked or running at reduced stocking levels (ACRIS 2008c). There is no data assessing the impact of change in ground cover and soil hydraulic properties due to cattle grazing on stream-flow regimes for the Fitzroy River catchment.

Land clearing

Land-clearing data in the Fitzroy River catchment could not be obtained, apart from the Australian Land Use Mapping dataset. ACRIS reports woody vegetation has either remained the same or increased at 70% of the monitoring sites located in the Central Kimberley bioregion. The Fitzroy catchment makes up a significant part (80%) of this bioregion (ACRIS 2008b). A number of stations in the region are planning land clearing for irrigation of fodder crops or improved pasture.

Fire

The area burnt is included in the Catchment Disturbance Index.

Surface water extraction

The Fitzroy River represents one of Australia’s last unregulated river systems. Many extraction scenarios are being considered, from three large catchment dams to isolated extraction from river pools for irrigation during the dry season. A weir pool for irrigation supply currently exists at Camballin and, although this impoundment has a negligible impact on wet season river flow, it may have a significant impact during the dry season. Farm dams are not extensive in the catchments, and are also likely to have a negligible impact on stream flow. The sustainable water yield is estimated to be 736 600 ML, while the current extraction is estimated to be 8685 ML, or 1 % of sustainable yield (AWRA 2005).

Ground water extraction

Licensed groundwater extraction is currently low in the Fitzroy region, particularly from the shallow alluvial aquifer but also from deeper Canning Basin aquifers. Surface–groundwater interactions are poorly understood in the Fitzroy catchment. There is, however, a current study addressing these knowledge gaps being undertaken by TRaCK, DoW and others).

5.3.6 Fitzroy River catchment: aggregation

There has been no modelling of pre- and post-disturbance in the Fitzroy catchment. Application of the FSR procedure was therefore not possible in the Fitzroy.

Only one hydrological class was represented in the Fitzroy—grazing with natural vegetation (See description in Table 5.3). In the Fitzroy it was assumed a sufficient level of grazing occurs by wild cattle in areas classed as conservation and natural environments.

Scores were aggregated to give a final hydrological disturbance theme score of **0.98** for the Fitzroy River SWMA (Table 5.14).

Table 5.14:Aggregation of hydrologic disturbance scores for each reach in the Fitzroy River catchment.

Hydrological class	No. of reaches	Total length (km)	Proportion of total reach network	Reach score	FARWH score
Grazing with natural vegetation	1191	11 900	1	0.98	0.98
Cleared land	0	0	0		
Urbanisation	0	0	0		
FSR	0	0	0		
Total	**1191**	**11 900**	**1**		**0.98**

5.4 Discussion

This trial adopted the FSR procedure (SKM 2005) to quantitatively assess the impact of anthropogenic disturbance on river hydrology in the wet/dry tropics. Modification of the methods was minor and only comprised adapting the period of reporting for three of the subindices to account for the region's highly seasonal, predictable pattern of rainfall and stream flow.

The FSR was applied to assess the impact of impoundments by Dixon et al. (2009) and shown to be responsive (Tables 5.15, 5.16; Figures 5.9, 5.10), and applied in the Daly to assess the impact of surface and groundwater extraction. There is no theoretical reason why the FSR procedure should not be applicable to the wet/dry tropics. Importantly, the subindices are ecologically relevant to the wet/dry tropics.

The FSR is suitable for rivers affected by dams and water extractions that alter the flow regimes and volumes. The method requires hydrographic data for pre- and post-impact periods. This is usually available where major water resource developments occur. For the most part, water resource development in the wet/dry tropics on regional and catchment scales is largely absent, though there are some notable local impacts such as the Ord River Dam in Western Australia and dams in the Gulf country of Queensland.

Future water resource developments are likely to have local, rather than regional impacts (CSIRO 2009a), and under current development scenarios could have their greatest impact on groundwater levels that supply dry season flows. The FSR can quantitatively score such impacts, assuming data availability. Such data requires more than hydrographic information, but also an understanding of surface–groundwater interactions (including extraction rates), the impact of groundwater extraction, and ultimately modifications to a catchment's water budget.

Catchment scale and regional impacts on hydrology are more likely to be linked to land use and management in the wet/dry tropics. These are principally cattle grazing, the effect of fire on catchment vegetation and the clearance of native vegetation and its replacement with pastures. These processes are poorly understood, but considered on the whole to be minor relative to water resource developments, and were estimated with a FARWH score marginally less than 1, based on expert opinion. This score, however, did not account for the possible increased frequency of episodic runoff events during the dry–wet transition period (see Townsend and Douglas 2000, Townsend et al. 2004), which can cause fish kills (Townsend et al. 1992) and may have other ecological impacts.

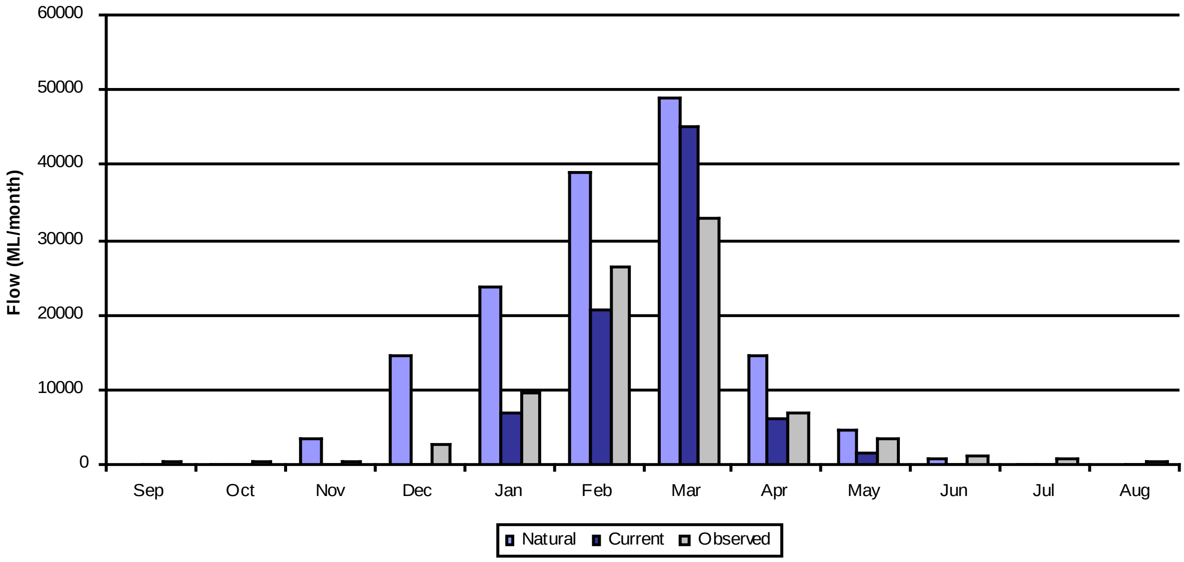
Where water resource developments occur, with a history of hydrographic data collection, the FSR procedure can provide a quantitative assessment of impact. This may not be the case, however, where groundwater extraction occurs and hydrologic impacts are not modelled. Water resource developments (impoundments and groundwater extraction) have a localised, though not necessarily ecologically insignificant, impact in the wet/dry tropics. Because of the large areas of the SWMA, their effect on the final FARWH score is 'diluted' and will not inform management of the hydrological degradation at the SWMA scale for the wet/dry tropics unless more detailed information is sought.

Table 5.15: Results for Darwin River *

Season	High flow	Low flow	Prop. of zero flow	Variation	Seasonal period	Avg.
Annual	0.38	0.65	0.99	0.55	0.43	0.60
Wet season (Dec.–Apr.)	0.48	0.00	0.99	0.50		0.49
Dry season (May–Aug.)	0.62	0.74	1.00	0.55		0.73
Groundwater stress (Sept.–Nov.)	0.62	0.83	0.95	0.01		0.60

***Modelled natural and current flow data generated from 1900 to 2002 by SKM (2006). Source: Dixon et al. 2009.**

Figure 5.9: Monthly average flows for Darwin River from Sept. 1962 to Aug. 1972 (G8150153)*



***Data from SKM (2006) and NRETAS; from Dixon et al. (2009.

Table 5.16: Results for Ord River.*

Season	High flow	Low flow	Prop. of zero flow	Variation	Seasonal period	Average
Annual	0.72	0.00	0.40	0.52	0.61	0.45
Wet season (Dec.–Apr.)	0.42	0.29	0.95	0.72		0.60
Dry Season (May–Aug.)	0.00	0.00	0.00	0.38		0.10

*** Modelled natural and current flow data generated from 1974 to 2005 (from Dixon et al. 2009).**

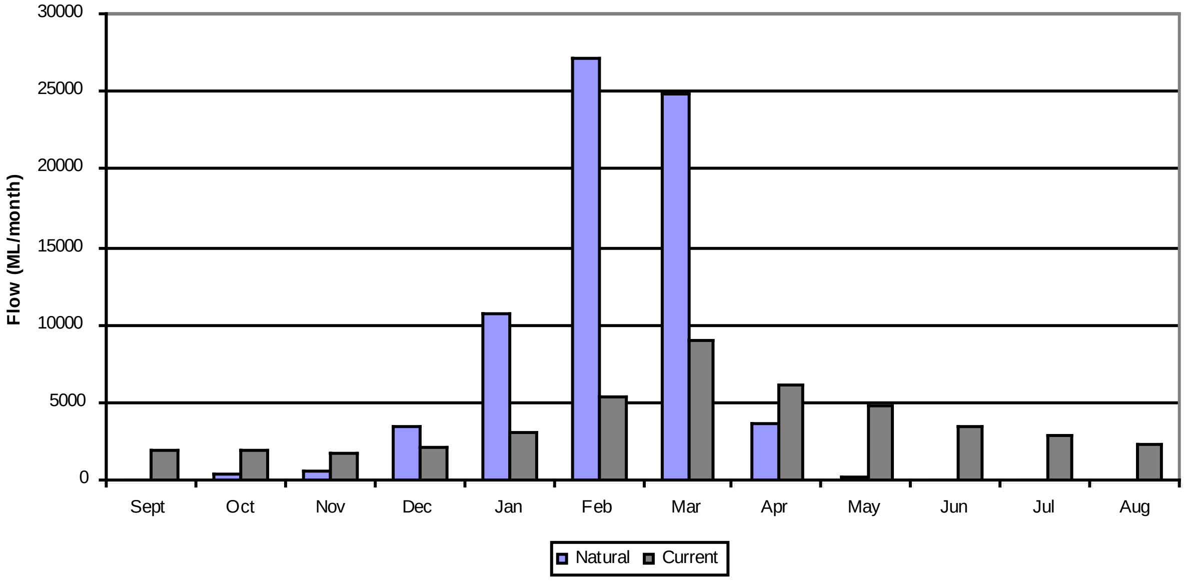


Figure 5.10: Monthly average flows for Ord River, downstream of the Ord Dam and the Dunham River confluence, 1974 to 2005 data from DoW (from Dixon et al. 2009).

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6 Water quality theme

6.1 Introduction

6.1.1 Background—threats to water quality in the Daly and Fitzroy River catchments

Anthropogenic pressures on water quality in the Daly and Fitzroy River catchments are principally diffuse in the wet season and point source in the dry season. The primary influences on water quality include, increased sediment loads associated with land clearing, grazing, agriculture and late dry season fires, and nutrient pollution from agricultural and pastoral land use. The impact that these pressures have on river water quality varies greatly between the wet and dry seasons. Additional pressures in the Daly River catchment are associated with water allocation, the overuse of fertilisers and pesticides and recreational use of rivers (Risby et al. 2009).

The water quality of rivers and streams is especially vulnerable to pollution during the dry season, when low flow conditions occur. Dry season flows are supplied by groundwater from both deep and shallow aquifers and, if polluted, may reduce the quality of surface flows for many years owing to the long lag time between groundwater contamination and its entry into rivers. In the Fitzroy River, pools are maintained by subsurface flow, with sand bars partitioning the river during the dry season.

Cattle and feral animals represent the primary catchment-wide pressure on water quality in both study catchments, and cause localised and downstream impacts, especially during the dry season. Ruprecht and Rodgers (1998) noted that the generally higher turbidity in the southern Fitzroy catchment may be due, in part, to greater grazing pressures.

This chapter applies the FARWH principles to the water quality theme. Compared to the other FARWH themes and their indices, the development of a water quality index for the wet/dry tropics is the least developed and most challenging. In developing a water quality index, the underlying principle is that the water quality attribute (e.g. dissolved oxygen), its metric (e.g. percentage saturation) and its interpretation (with respect to the reference condition) is ecologically relevant, and can be scored between 0 and 1.

6.1.2 Context of water quality data collection for the wet/dry tropical FARWH

Three subindices were considered for the water quality theme. These were: 1) wet season sediment and nutrient loads, 2) wet–dry transition water quality, and 3) dry season (June–September) base-flow water quality.

Sediment and nutrient loads were calculated for the National Land and Water Audit. A load subindex, however, was not included in the tropical FARWH, because 1) flow data was not readily available for Western Australia and 2) little data exists on sediment and nutrient loads in the Northern Territory. In the Northern Territory a SEDNET model, which computes sediment load, has been developed for the Daly River catchment. However, the model's predictions need to be tested before being incorporated into state agency work programs. In the wet/dry tropics most, if not all, of the annual fluvial load occurs during the wet season's major flood events. Much of the sediment transported during the wet season is flushed from the catchment and deposited in sedimentary environments in the estuary and near shore marine habitats. Catchment loads (mass per unit time) are thus relevant to land and estuary management. However, from an in-stream ecological perspective, they have lesser direct significance for freshwater biota.

Sampling during the transition between the wet and dry seasons has been used to monitor pollution from mine sites (e.g. Rum Jungle mine, Finniss River). At this time of year, dilution from major storms is reduced, relative to the wastewater discharge, and water quality impacts are potentially elevated. Sampling during this seasonal transition was not undertaken in this study because much of the stream network remains inaccessible and because the period of transition between elevated wet season flows and low or cease-to-flow conditions is often brief.

Water quality sampling is most efficiently conducted during the dry season when the river channel is accessible and stream flows are low. Potential threats to water quality are concentrated during the dry season when flows are lowest, in comparison with the large, diluting and highly variable flows characteristic of the wet season. Thus the index 'dry season base-flow water quality' has been chosen for the FARWH assessment for the wet/dry tropics.

Dry season water quality

During the dry season, surface water quality can be influenced by both groundwater quality and in-stream process. Often the quality of surface water during the dry season remains consistent, due to the influence of groundwater quality. For example, weekly monitoring of the Edith River in the Daly River catchment (Figure 6.15) revealed low variability of all measured attributes (Table 6.1), particularly when viewed from an ecologically significant perspective. In contrast, in-stream processes such as primary productivity can influence dry season water quality substantially, particularly during cease-to-flow events. Under these static conditions, elevated water temperatures and light availability can increase biological activity resulting in, among others, large variations in dissolved oxygen concentration. Anthropogenic influences, including the input of nutrients and sediments from, for example, cattle accessing the riparian corridor and the water's edge, can exacerbate primary productivity to levels that result in ecologically important shifts in water quality.

Figure 6.15: Edith River site of seven weeks consecutive sampling. Upstream (left), downstream (right).

Table 6.28: Mean water quality conditions (nutrients, conductivity, turbidity; pH median) and standard errors, at two nearby sites in the Edith River, over seven consecutive weeks during the dry season 2009. (Site results were grouped to average).

Water quality attribute	Metric	Mean (median pH)	Std. error
pH		6.49	-
Conductivity	µS/cm	14.2	± 0.38
Turbidity	NTU	1.21	± 0.37
Total phosphorus	µg/L	5.8	± 0.9
Total nitrogen	µg/L	64	± 4.7
NO_x	µg/L	4.4	± 2.9
PO_4	µg/L	2.9	± 0.7

6.2 Methods

6.2.1 Water quality field data collection for FARWH wet/dry tropics

Water quality attributes considered

The water quality attributes considered for use are described below in Table 6.29.

Table 6.29: Status and application of potential water quality attributes and metrics considered.

Attribute	Measurement and metric	Ecological relevance	Comments	Applied
pH	Field instrument. Metric: pH units.	Solubility of metals and their toxicity—directly affects cell functioning of some biota cell functions (e.g. oxygen transfer across gills).	Best accompanied by measurements of acidity and alkalinity to provide information about the amount of acid/alkali. A low pH could result from low concentrations of fluvic acids and be relatively harmless, or be due to sulphuric acid, which is highly corrosive. pH varies diurnally, though only notable in rivers with high primary production.	✓
Metal concentrations	Water sample for laboratory analysis. Can require field filtration and preparation. Different metal analyses possible. Metric: concentration.	Toxic in high concentrations.	When accompanied by pH and alkalinity, the toxicity of the metal can be inferred. Consideration required for the form that the metal is present (total, soluble, valence type).	X
Pesticides	Water sample for laboratory analysis. Metric: concentration.	Toxin.	Suite of pesticides required. Analysis expensive.	X
Electrical Conductivity	Field measurement. Metric: electrical conductance	Salinity.	Salinity is inferred from conductivity rather than measured directly. Conductivity provides information about aquifer source.	✓
Temperature	Field measurement. Metric: °C.	Determines dissolved oxygen concentration, microbial and other	Varies diurnally. Required to determine the percentage saturation of dissolved oxygen.	X*

Attribute	Measurement and metric	Ecological relevance	Comments	Applied
		poikilothermic rates of metabolism. Water temperatures sensitive to clearance of river canopy cover.		
Dissolved oxygen	Field measurement of diurnal dissolved oxygen concentration and temperature (for latter metric). Metric: concentration and percentage saturation.	Required for biotic aerobic metabolism. Product of photosynthesis.	Varies diurnally. Can be influenced by altitude and salinity.	✓
Plant nutrient: phosphorus	Water sample for laboratory analysis of soluble (FRP) and total P. Field filtration may be required. Metric: concentration.	Plant nutrient required for metabolism and growth.	Only relevant if phosphorus limits plant growth. Soluble P provides an indication of the P available for plant uptake, while total P can include organic P and P absorbed to minerals, which is not available for plant uptake. Low FRP can be naturally low or due to high rates of plant uptake, which may or may not meet plant requirements.	✓
Plant nutrient: nitrogen	Water sample for laboratory analysis of nitrate, nitrite, ammonium and organic N. Metric: concentration.	Plant nutrient required for metabolism and growth.	Only relevant if nitrogen limits plant growth. Ammonium and nitrite generally below detection limit in the well-oxygenated waters in the NT study catchments. Nitrate can be naturally low or low due to high rates of plant uptake, which may or may not meet plant requirements. Total N comprises mainly organic N not readily available for plant uptake.	✓
Water clarity	Field measurement. Metric: turbidity (NTU).	Reduction of light through water column to river bed.	Light transmission can also be reduced by colour (dissolved humic substances). Light penetration to the riverbed is also dependent on water depth. A high turbidity in shallow water may produce the same incident light at the riverbed as a clear, deep stream.	✓

X* Temperature not used as indicative attribute but must still be measured to calculate dissolved oxygen.

Of the above water quality attributes considered for developing the FARWH water quality theme score, the following were chosen:

- electrical conductivity (μS/cm)
- pH
- turbidity (NTU)
- dissolved oxygen (% saturation and mg/L)
- nitrogen (μg/L) (Daly—nitrate and total nitrogen; Fitzroy–total nitrogen)

- phosphorus (μg/L) (Daly—filterable reactive and total phosphorus; Fitzroy- total phosphorus).

Temperature, metal and pesticide concentrations were not used for the tropical FARWH field trials. In temperate regions, clearing of riparian vegetation can elevate daily maximum water temperatures. In the study catchments, however, the clearing of riparian vegetation is not considered a prime management issue and in the Northern Territory is illegal. Additionally, unlike the forested reference conditions of upper reaches in southern Australian river systems, the headwaters of the Katherine/Daly system flow through 'stone country' landscapes and do not always have thick vegetation cover. Furthermore, river channels with higher stream orders in wet/dry tropical catchments tend to be wide, and the generally sparse riparian vegetation provides minimal shading to the water surface. Consequently, typical assumptions of the importance of riparian vegetation in controlling water temperatures are not necessarily appropriate the wet/dry tropics.

Metal and pesticide sampling were not considered cost effective for catchment-wide river health assessment; instead the resources were directed to measuring the parameters identified above within the subcatchments of concern. Where mine discharges to a river are being sampled, metals, alkalinity and possibly major cations and anions could also be sampled.

FARWH water sample collection and analysis

In the Daly River catchment, water quality data was recorded from 41 sites between June and October 2009, before end-of-dry-season storm runoff. Spot measurements were taken of pH, conductivity, temperature and dissolved oxygen (DO) using a Quanta multi-parameter probe. Turbidity was measured using a Hydrolab Hatch turbidimeter 2100P. Samples were also collected for laboratory analysis of nutrients and subsequently analysed for total nitrogen (TN), NOx (nitrate and nitrite), total phosphorus (TP) and filterable reactive phosphorus (FRP). At 29 sites a calibrated Hydrolab Datasonde was used to measure in situ dissolved oxygen, temperature and turbidity over several days.

In the Fitzroy River catchment, water quality data was recorded at 34 sites, distributed throughout the catchment, between July and September 2009. A calibrated Hydrolab Datasonde was used for in situ measurements of conductivity, salinity, ORP, pH, temperature, DO and turbidity. Secchi depth was also measured. Samples were collected for laboratory analysis of nutrients as for the Daly. Dissolved oxygen meters (TPS WP82) were placed at 14 sites for a minimum of 24 hours to record diurnal changes in dissolved oxygen and temperature. Although not all of the measured water quality parameters were required for the water quality theme, they were recorded to contribute to the limited knowledge on variability in water quality ranges in the Fitzroy River. Additional water quality parameters were also measured to supplement fish and macroinvertebrate models used in the aquatic biota index.

6.2.2 Approach of FARWH water quality index.

The development of a water quality theme index for the Daly and Fitzroy river catchments was constrained by a lack of knowledge about the ecological implications of water quality deviations from reference conditions. Understanding of the deviation from reference condition represents the foundation of the FARWH water quality theme. Reference conditions for water quality parameters, and scoring bands to assess the departure from reference conditions were established, based on a review of current literature and the use of expert knowledge. The potential ecological significance of changes in water quality parameters formed the basis of this approach. The aim of this assessment was to develop a water quality index that was transparent and simple to understand, and that reflected the ecological significance of changes in water quality.

The following steps outline the logic taken in deriving the FARWH water quality index.

Step 1. Determine reference condition—the natural range or ‘reference’ conditions for the water quality attribute. Percentile values were calculated, as recommended by the water quality management strategy (WQMS), to provide information about the reference condition.

Step 2. Derive ecological disturbance thresholds, bands and scores—to assess whether deviations above or below the reference condition range have significant ecological implications or whether it was likely that the river’s ecosystem was adapted to deviations beyond the range of reference values. If no ecological significance could be discerned, then values that deviated beyond the natural range (to a specified maximum) were scored equivalent to the reference condition, i.e. a value of 1.

If the ecosystem was not likely to be adapted to deviations from the reference range, then bands beyond the natural range were established and assigned scores. The number of bands was kept to a minimum to reflect the limited understanding of ecological response, and/or ecological thresholds to changes in water quality. The disturbance bands were largely based on multiples of the reference condition and are likely to reflect ecological impacts.

Step 3. Aggregation—combine all measured and scored water quality attributes into a final score for the site and reach.

6.2.3 Application of FARWH water quality index

Step 1—Determining reference condition

Daly River catchment.

The variability of all water quality attributes, except dissolved oxygen, was assessed using historical water quality data. Data was drawn from multiple projects (NRETAS and TRaCK, Appendix 13.4), and limited to three dry season months (July–September). The catchment was divided into broad river sections based on expert knowledge of catchment conditions, including geology, aquifer source, groundwater movements, diffuse and point source impacts, and the river drainage system. There were issues associated with this such as a lack of data for some sections and other sections that were classified as ‘water quality transition zones’ between aquifer sources. In transition zones, water quality characteristics were varied along a longitudinal and temporal gradient and could not be readily used to define reference conditions. Twelve broad river sections were initially identified. PCA analysis by PRIMER was performed using conductivity, turbidity and soluble nutrients (nitrate and phosphorus) data for each river section (Figure 6.2) From these results, as well as considering box plots of each attribute in each river section, the 12 initial river sections were reduced to seven (Figure 6.2, Table 6.3). To illustrate the constraints of the limited data available for some river sections, the number of data available for determining reference conditions for each river section is shown in Table 6.31.

Table 6.2: Daly River and tributary river sections.

River sect.	River section name
1	Katherine up/s Donkey Camp
2	Katherine lower (Galloping Jacks to Flora confluence)
3	Limestone Ck
4	Flora
5	Fergusson
6	Daly to Douglas confluence
7	Stray (upper)
8	Stray (lower)
9	Douglas lower to Hayes confluence
10	Douglas up/s to Depot Ck
11	Hayes Ck
12	Daly–Douglas confluence to Daly Crossing

Figure 6.16:PCA analysis using turbidity, nitrate (NO3_N), filterable reactive phosphorus (FRP) pH and conductivity (log) for 12 perennial river sections in the Daly River catchment.

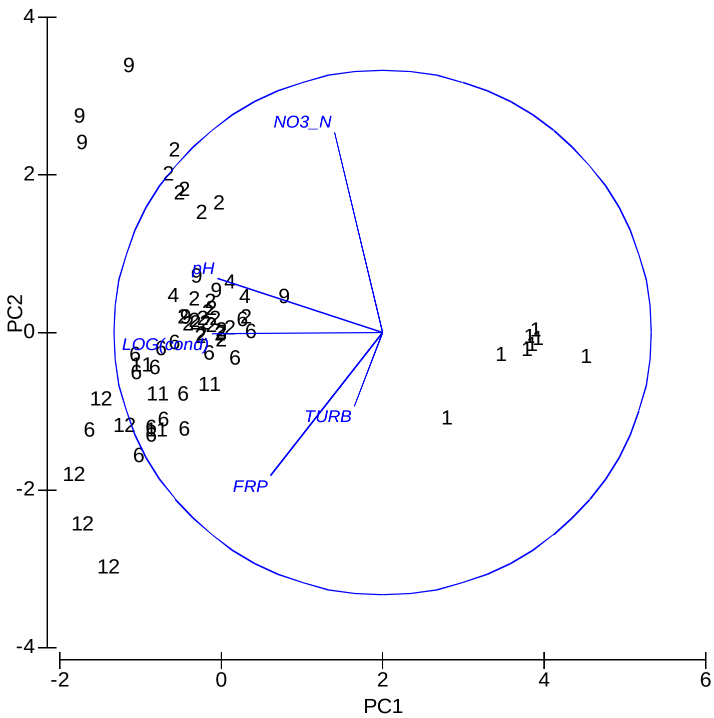
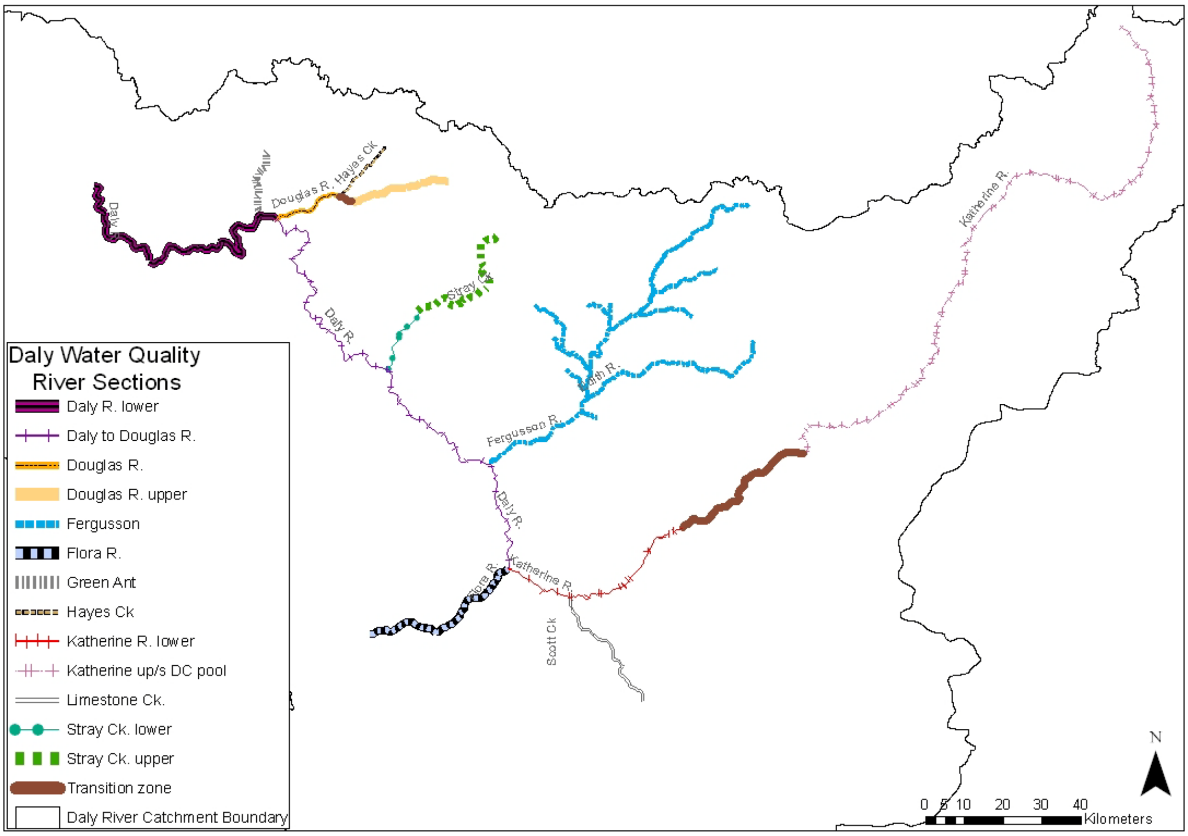


Figure 6.17: Daly catchment river sections used for determining FARWH water quality reference condition.*



***Transition zones were excluded. Green Ant region was not considered to be in reference condition.**

Table 6.30: Final river sections and the major reaches included within each derived for FARWH scoring of the Daly Catchment.

Sandstone country	Lower Katherine	Limestone	Flora	Daly upper	Lower Douglas	Daly lower
All upper reaches derived from Tindal limestone aquifer. Includes: Douglas upstream, Katherine upstream of Donkey Camp, Fergusson and Stray Ck upstream.	Katherine river, downstream of transition zone (i.e. below Galloping Jacks) to confluence with the Flora River.	Unique tributary into the lower Katherine.	Unique river, which joins the Katherine to become the Daly River.	Begins at confluence of Flora and Katherine rivers, to confluence of Daly and Douglas rivers. Also includes: Stray Ck downstream and Hayes Ck.	Douglas River from confluence with Daly to confluence with Hayes Ck upstream.	Daly-Douglas River confluence to the Daly River Crossing.

Table 6.31: Final river sections and number of data of each water quality attribute, sampled by spot measurements.

Water quality attribute	Sandstone country				Lower Katherine	Lime-stone	Flora	Daly upstream			Lower Douglas	Lower Daly
Sections grouped	Douglas u/s	Katherine i/s	Fergusson	Stray u/s				Daly upper	Stray lower	Hayes		
Conduct-ivity	12	76	42	3	73	2	41	95	2	7	20	34
pH	12	93	43	3	73	2	41	96	2	7	20	39
Turbidity	10	59	30	3	42	2	11	59	2	8	19	33
Nutrients: TN	0	16	20	3	2	4	11	43	2	4	2	3
TP	11	59	20	5	2	4	14	80	4	6	26	39
NO3_N	1	46	11	2	30	2	13	47	2	4	18	23
FRP	6	47	25	5	44	4	12	70	4	6	19	35

A WQMS approach was used to guide the selection of reference conditions for each river section. This exercise was carried out for FARWH, but also with the intention to assist in the future development of water quality guidelines for the Daly River catchment. This is timely following the recent publication of the report: *Towards a water quality monitoring and management framework for the Katherine and Daly River catchment* (Risby et al. 2009), which recommends key steps towards developing a monitoring and management framework for the catchment.

The 95th percentile was used to establish trigger values for each water quality parameter in each river section (Appendix 13.5). This approach was modified following the conceptual approach of the Australia and New Zealand Environment and Conservation Council (ANZECC) guidelines (2000) and other WQMS approaches, which derive trigger value thresholds from the 20th and 80th percentiles of reference data. Where there was insufficient data for some reaches, the maximum was used. Given the largely undeveloped nature of much of the Daly waterways, the 95th percentile value for each attribute (except for pH) was doubled to create the reference condition band. The resulting value represented a precautionary value that allowed for some level of change that was unlikely to result in an ecological effect. Reference ranges for pH in Daly River sections were defined using maximum and minimums of historical data.

Fitzroy River catchment

Historical water quality data was summarised for all attributes in order to derive percentiles from reference data (as per section 6.1.3). Data available from 34 gauging sites registered on the Department of Waters WIN database was classified into the subregions defined for the Fitzroy River field trials (upper, lower and small tributaries) and limited to the dry season months of the year, July–September.

Collation of this dataset revealed severe limitations in the quantity of data available for each of the water quality parameters required to calculate a water quality theme score (Table 6.32).

Table 6.32: Summary of WIN gauging-station data available for the Fitzroy catchment highlighting the number of data points available for each attribute

Catchment region	Attributes			Nutrients			
	Sp Cond. (µS/cm)	pH	Turbidity (NTU)	FRP (mg/L)	NO_3 (calc) (mg/L)	Total P (mg/L)	Total N (mg/L)
Lower	14	2	3	0	1	4	2
Middle	30	3	8	0	1	7	7
Upper	18	3	6	0	0	2	4
Other	30	6	7	0	0	7	0
Total	92	14	24	0	1	20	13

The paucity of water quality records available for the Fitzroy River was also confirmed by a survey by Van Dam (2008), who summarised:

> …..There is little published literature on the water quality of the Fitzroy River. Moreover, Butler (2008) concluded that existing WA Government water quality monitoring data for the Fitzroy River, whilst available for 17 sites, were insufficient to properly analyse spatial and temporal (seasonal) water quality characteristics.

With insufficient data for the Fitzroy River, there were substantial limitations for adopting the preferred methodology of setting reference condition based on percentile ranges of historical data (see above). Firstly, using the only historical data available (WIN database) there is no scope to isolate reference sites. Water quality measurements are not collected systematically, significantly reducing the number of sites available, and knowledge surrounding the natural variation in the catchment, and moreover in the Kimberley region, is extremely limited.

Alternative methods for setting reference criteria were explored, including the methodology used for setting reference sites for the aquatic biota theme (Chapter 9). This method was considered inappropriate for setting reference criteria for water quality as the pressure and condition scores on which reference conditions were established were defined at a site-specific scale. Water quality parameters, more specifically salinity and pH, will be determined at a subcatchment scale (i.e. based on variations in soils, slope or rainfall and runoff patterns). As water quality at individual sites is likely to be influenced at a broader spatial scale (e.g. upstream catchment), it was assumed that this method was inappropriate for determining reference conditions for water quality. The most appropriate technique for determining reference conditions requires historical and local knowledge of the natural variations and ranges across the subcatchment. A review of current literature revealed that data and specific knowledge on these variations were scarce in both the Fitzroy River and, more generally, the Kimberley region.

The decision was therefore made to set rudimentary scoring bands guided initially by the ranges and percentiles calculated from the only historical data source available: the WIN database. These preliminary band levels were then refined using literature reviews on aquatic biota tolerances, data from ad hoc surveys throughout the catchment (e.g. AUSRIVAS) and expert knowledge of water quality and ranges in neighbouring catchments. It should be noted that all available data was analysed and not limited to specific reference sites and that no data was available for tropical WA estuaries or rivers when determining ANZECC guidelines

(2000).

A discussion of each of the water quality attributes and justifications for the ranges chosen is provided below.

Step 2—Deriving bands of disturbance (ecological effect) and scoring for FARWH

This was carried out using a combination of approaches, making use of:

- existing data:
    - Daly—using the reference condition data (from short term data sets)
    - Fitzroy—using the only available long-term data set (WIN database) supplemented by ad hoc data sets and data sets in neighbouring catchments
- literature reviews
- expert knowledge.

Each water quality attribute is considered separately below. For the Daly River it was not deemed necessary to create separate bands for each river section for water quality components. Where appropriate, river sections were combined (for example, nutrients, pH, DO). For the Fitzroy, the catchment was divided into separate subregions when there was sufficient data or knowledge to suggest natural variations in the water quality parameter existed.

The waters of the Daly and Fitzroy river catchments are both naturally low in nutrients and have low conductivity and turbidity, and therefore no lower limits have been set for these water quality indices. Lower limits have been specified for only pH and dissolved oxygen in both catchments.

Electrical conductivity

Unlike temperate Australian catchments, the Daly and Fitzroy river catchments are not at risk of dryland salinity. Ecological disturbance resulting from saline toxicity is perhaps of less significance to the wet/dry tropical catchments. It does, however, reveal information about the aquifer source and potential land-use impacts (mining discharge, aquifer contamination).

The FARWH scoring bands for conductivity in the Daly and Fitzroy rivers are shown in Tables 6.6 and 6.7 respectively. Conductivity is the water quality parameter that primarily distinguishes river sections within the Daly River catchment. Generally, conductivities greater than 1000 µS/cm could be expected to have some low level of ecological impact, while conductivities greater than 3000 µS/cm could result in a more significant ecological impact (Tables 6.6, 6.7).

In the Fitzroy River catchment, analysis of historical data revealed differences between conductivity in the upper tributaries and conductivity in the rest of the catchment. Preliminary values of 500 µS/cm and 1400 µS/cm respectively were established, based on the 95th percentiles. Minor ecological impacts were therefore predicted for conductivities of 900–2250 µS/cm for upper tributaries and 2800–7000 µS/cm. In relation to the ANZECC guidelines, the FARWH reference-band values are much higher than the national guidelines, with the exception of the Sandstone country river sections in the Daly River (Table 6.8).

Table 6.6: FARWH River section scores for conductivity in the Daly catchment.

Scoring band for river section	Sand-stone coun-try	Kath-erine (lower)	Lime-stone	Flora	Daly (upper)	Douglas (lower)	Daly (lower)	FAR-WH score	Cat-egory
2 x 95th percentile (rounded)	100	1200	2600	1700	1200	1100	1300	1	Refer-ence
5 x 95th percentile (rounded)	>100-350*	>1200-3000	>2600-6600	>1700-2000	>1200-3000	>1100-2700	>1300-3000	0.5	Low disturb-ance
> 5 x 95th percentile (rounded)	>350	>3000	>6500	>2000	>3000	>2700	>3000	0.25	High disturb-ance

(*round to nearest 50, all others rounded to nearest 100)

Table 6.7: Scoring bands for conductivity (µS/cm) determined for the Fitzroy catchment.

Scoring band for catchment	Upper tributaries	All other sites	FARWH score	Category
2 x 95th percentile (rounded)	0–900	0–2800	1	Reference
5 x 95th percentile (rounded)	901–2250	2801–7000	0.5	Low disturbance
> 5 x 95th percentile (rounded)	>2250	>7000	0.25	High disturbance

Table 6.8: FARWH values indicating low level disturbance and National ANZECC trigger value guidelines.

Source	Year	Region/river section	Electrical conductivity (EC µS/cm)
ANZECCC default guidelines (tropical Australia)	2000	Upland and lowland river	20–250*
FARWH (low-disturbance level)	2010	Daly–sandstone origin	>100
		Daly–Tindal limestone origin (lower Katherine and Douglas)	>1100
		Daly–other	>1200
		Fitzroy–upper tributaries	>900
		Fitzroy–other	>2800

Dry season flows in much of the Daly catchment originate from three aquifers: the Cretaceous sandstone, the Oolloo dolostone and Tindal limestone aquifers. The latter two aquifers provide a large proportion of total dry season flow for the Daly and Douglas rivers. Waters from these aquifers have conductivities of 500–600 µS/cm (Tickell 1997), and also supply higher conductivity rivers such as Limestone Creek. In contrast, groundwaters feeding the upper reaches of the Katherine and Douglas rivers are from the Cretaceous aquifer and characterised by low conductivity (<50µS/cm) (Tickell 1997).

For the Fitzroy River, analysis of the limited historical salinity recordings (WIN database), revealed a distinct difference between the upper tributaries and the rest of the catchment. This was supported by a TRIAP review of water quality, which noted;

> Ruprecht & Rogers (1998) provided a very broad overview of salinity…the salinity ranges from ~0.07–0.7 ppt in the lower rainfall (<600 mm/year) catchments and ~0.03–0.5 ppt in the higher rainfall catchments (>600 mm/year).
>
> Water physico-chemical data collected as part of the AusRivAS program in the Fitzroy River provides some indication of water quality. River/creek electrical conductivity (EC) and alkalinity range from ~30–800 µS/cm and ~10–250 mg/L CaCO3, respectively…although data are limited, streams in the headwaters of the Fitzroy River, such as the Hann River, appear to have the lowest EC (~40 µS/cm) and alkalinity (~10 mg/L CaCO3), which corresponds to the sandstone geology of the northern-most part of the Fitzroy catchment.

Changes in salinity (inferred from conductivity) can alter the solubility of ions, pH, and reduction and oxygenation potential of waters (Dunlop et al. 2005). It is worth considering pH with conductivity. A highly alkaline solution has an increased buffering capacity (ability to accept H+ ions) and therefore waters naturally high in alkalinity are less likely to be affected by increases in acidic salts (Dunlop et al. 2005). In the Daly River catchment, the Flora and Limestone rivers flow largely through limestone country and are examples of rivers with naturally high alkalinity.

Dunlop et al. (2005, 2007) summarise the knowledge to date on freshwater biotic tolerance to salinity, including that for tropical waters in Queensland. In Queensland, nine water types were identified, based on similarities in the percentage of major ions (Na^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, SO_4^{2-}) and found to be consistent with geology, climate and proximity to the ocean

(McNeil et al. 2005 in Dunlop and McGregor 2007). Given the influence of geochemistry in the Daly, the composition of ions in each river section is worth considering.

The ratio of sodium and potassium (Na^+ and K^+) to magnesium and calcium (Mg^{2+} and Ca^{2+}) is an important determinant of the toxicity of salts. Higher proportions of sensitive taxa could thus be found in calcium bicarbonate-dominated water than in sodium chloride-dominated water under equal conductivities. Alkalinity is necessary for applying the AUSRIVAS model for macroinvertebrate analysis but was not collected during the trials. Conductivity was used as a substitute, given the strong relationship between the two ($r^2 > 0.80$). Waters low or high in alkalinity might, for example, reflect depauperate or rich mollusc fauna respectively. Similarly, high acidity might result in low mollusc and crustacean fauna.

Freshwater fish appear quite tolerant of salinities up to about 1000 mg/L (14 705 µS/cm) (Hart et al. 1991). There is some evidence of freshwater fish being more sensitive during the early life stages (for example non-hardened eggs are particularly sensitive) (Clunie et al. 2002). The salinity tolerances for several species found in the Daly and Fitzroy catchments, as well as several with representatives from the same family, are shown below (Table 6.9, adapted from Dunlop et al. 2005). All of these tolerance thresholds are well above the FARWH scoring bands. The species *Melanotaenia splendida* occurs in the Daly and one toxicity study found an acute LC_{50} of 4400 µS/cm. This is the threshold value closest to that of the established FARWH scoring bands for fish, but still higher than the average FARWH threshold for the Daly, and falls within the 'low disturbance' band for the Fitzroy.

Table 6.9: Salinity tolerance of freshwater fish found in the Daly and/or Fitzroy (*) or with a representative in the same family.*

Species name	Common name	Direct (acute) LC_{50} (µS/cm)	Slow (chronic) LC_{50} (µS/cm)	Early life stage LC_{50} (µS/cm)	Same species found in Daly (SpD), Fitzroy (SpF) or representative of same family in Daly (famD), Fitzroy (famF)
Hephaestus fuliginosus	Sooty grunter	-	-	11 800 10 300	*H. jenkinsi* (famF) *H. bancrofti*.(famF)
Morgurnda adspersa	Purple-spotted gudgeon	21 800	-	-	*M. Morgurnda* (SpD) *M. oligolepis* (famF)
Melanotaenia splendida splendida	Eastern Qld rainbow fish	13 200 **4400**	26 200	25 000 13 200	*M. splendid australis* (SubSpD), *M. splendid inornata* ((SubSpD, SubSpF) *M nigrans* (famD, famF)
Melanotaenia fluviatillis	Crimson spotted rainbowfish	44 100 31 000	43 800	25 000 17 600	
Leiopotherapon unicolour	Spangled perch	32 400	52 200	-	*L. unicolour* (SpD, SpF)
Craterocephalus stercusmuscarum	fly-specked hardyhead	64 300	-	-	*C.stercusmuscarum* (SpD) *C. stramineus* (famD)

***Most sensitive value highlighted in bold. (adapted from Dunlop et al. 2005 and Clunie et al. 2002).**

Hart et al. (1991) found salinities in excess of 1470 µS/cm (1000 mg/L) were likely to result in observable adverse effects in macroinvertebrate communities. Similarly Brock et al. (2005) found decreased emergence and hatching of aquatic zooplankton and plant seeds as salinity increased above 1000 mg/L. This threshold is consistent with the FARWH scoring bands for low disturbance in the Daly and upper tributaries of the Fitzroy. Distinctive shifts in communities (from sensitive to more tolerant species) were observed to occur from 800 to 1000 µS/cm for edge habitats in Queensland and lower (~300 µS/cm) for riffle habitat (Dunlop et al. 2005). The edge habitat range is again close to the threshold between reference and low disturbance scoring bands for five out of seven of the Daly River Sections and the upper tributaries of the Fitzroy.

A more recent study aimed at testing the applicability of tolerances derived for temperate species to that of tropical species (east coast Australia) found the tolerance range of freshwater macroinvertebrates in north-east Australia (72h LC_{50} values ranging between 6900–55 000 µS/cm) consistent with previous studies in the south-east (Kefford 2003, 2006, in Dunlop et al. 2008). These thresholds are much higher than most of the FARWH scoring bands for disturbance but the lower limit (6900 µS/cm) is close to the threshold for the highly disturbed scoring band for lower tributaries in the Fitzroy.

As reviewed in Dunlop et al. (2005), a large proportion of aquatic macrophytes are sensitive to salinity at concentrations between 1470–2941 µS/cm, above which growth and reproductive success are likely to be significantly reduced. The upper value of this range is close to the high disturbance scores (>3000 µS/cm) for most river sections in the Daly River catchment and the upper tributaries of the Fitzroy River catchment.

pH

The FARWH scoring bands for pH in the Daly and Fitzroy rivers are shown in Table 6.10 and 6.11 respectively.

Table 6.10: Scoring bands for pH in sandstone and 'all other' river sections of the Daly catchment.

River section		FARWH score	Category
Sandstone	All other		
<4.0	<6.0	0.25	High
4.0–4.4	6.0–6.9	0.50	Moderate
4.5	7.0	1.00	Reference
7.5	8.5	1.00	Reference
7.6–8.5	8.5–9.0	0.50	Moderate
>8.5	>9.0	0.25	Low

Table 6.11: Scoring bands for pH in the Fitzroy River catchment.

Catchment	FARWH score	Category
<6.0	0.25	High
6.0–7.0	0.50	Moderate
>7.0	1.00	Reference
9.0	1.00	Reference
>9.0–9.5	0.50	Moderate
>9.5	0.25	High

The pH of streams in the Daly region is naturally lower in the sandstone country of the upper reaches. Limestone creek had values above 8. The scoring bands in the Daly were based on the range and 95th percentile of historical data.

For the Fitzroy River catchment, the FARWH scoring bands for pH were informed from WIN database percentiles and ranges. These levels were consistent with the work of Morgan et al. (2000) that recorded an (arithmetic) mean pH across the catchment of 8.17 and all of his survey sites, with the exception of one site, were recorded as alkaline.

There is a substantial lack of case studies examining the effect of pH on tropical freshwater biota. It is worth considering pH in relation to conductivity as there is the potential to detect impacts from mine discharge when the two parameters are examined together. Acidification is known to affect the solubility of metals such as aluminium. For example, as pH decreases below 6.0, aluminium becomes increasingly soluble and potentially more toxic to freshwater biota (Gensemer and Playle 1999 in Camilleri et al. 2003). Thus, in Daly River sections with naturally low pH waters, the risk of mobilisation of metals should be considered with new or changing land uses.

When conductivity is high and pH simultaneously low it is likely to represent acidic pollution from a mine. Thus an extra caveat is worthy of inclusion:

If conductivity >3000 and pH <4.5, the site gets a FARWH score of 0.25.

Water clarity

The FARWH scoring bands for turbidity in the Daly and Fitzroy rivers are shown in Table 6.12 and 6.13 respectively. Base-flow turbidity is naturally low (less than 20 NTU), so no lower limit was considered necessary for turbidity in either of the catchments. Low disturbance threshold values ranged from 10–30 NTU for river sections in the Daly River, while for the Fitzroy River, the same band was set at 50 NTU.

The high disturbance thresholds are consistent with values in the limited available northern Australian literature, which suggest an ecological effect occurs when turbidity exceeds 30 NTU (Stowar 1997). The reference ranges are also consistent with ANZEC guidelines set at a background level of 2–15 NTU (Table 6.14).

Table 6.12: Scoring bands for turbidity (NTU) in the Daly River catchment.

Scoring band for river section	Sand-stone country	Katherine lower	Flora and limestone	Daly upper	Douglas to Hayes Ck	Daly lower	FARWH score	Category
2 x 95th percentile (rounded)	20	10	15	10	10	15	1	Reference
5 x 95th percentile (rounded)	21–60	11–15	16–35	11–20	11–20	16–35	0.5	Low disturbance
> 5 x 95th percentile (rounded)	>60	>15	>35	>20	>20	>35	0.25	High disturbance

Table 6.13: Scoring bands for turbidity in the Fitzroy River catchment.

Scoring band for catchment	Turbidity (NTU)	FARWH score	Category
2 x 95th percentile (rounded)	20	1	Reference
5 x 95th percentile (rounded)	21–50	0.5	Low disturbance
> 5 x 95th percentile (rounded)	>50	0.25	High disturbance

Table 6.14: Minimum FARWH values indicating disturbance and national trigger value guidelines.

Source	Year	Region/river sections	Turbidity (NTU)
ANZECC default guidelines (tropical Australia)	2000	Upland and lowland river	2–15
FARWH	2010	Daly–sandstone origin Fitzroy	>20
		Daly–Tindal limestone origin (lower Katherine and Douglas)	>10
		Daly–other (flora, limestone, Daly lower)	>15
		Fitzroy	>20

As described above, the Daly River catchment was divided into river sections following analysis of historical data at the 95th percentile. In the Fitzroy River catchment, only 24 historical recordings of turbidity were available, giving a 95th percentile of 10.5 NTU. Although TRIAP speculated that higher turbidity readings recorded in the southern portion of the Fitzroy River catchment may be due, in part, to i) greater grazing pressures in the southern catchments and ii) the northern catchments being predominantly 'hard rock' and less erodible, there was insufficient data to provide ranges of turbidity for separate regions.

As reported in Dunlop and McGregor (2007), it is very difficult to define standard sediment exposure tests to assess sediment impacts and very little work has been done in Australia. A preliminary study in the Northern Territory on the effect of fine suspended sediment on billabong limnology by Buckle et al. (2010) found phytoplankton production appeared to be inhibited at turbidity values around 50 NTU. However, the study required more samples above 30 NTU in order to better define the relationship (Buckle et al. 2010). The 50 NTU threshold aligns with the low disturbance category in the Fitzroy River and low to high disturbance categories in the Daly River.

Two reports by Stowar (1997) and Stowar et al. (1997) examined the effect of elevated turbidity levels on macroinvertebrates and found some disturbance in communities at levels of 30 NTU. Stowar et al. (1997) found turbidity was observed to rise to levels averaging 60 NTU immediately downstream of a road crossing in Kakadu National Park, where the water clarity averaged a background level of less than 5 NTU, while one kilometre downstream the average level of turbidity was approximately 30 NTU. Observed turbidity levels were strongly correlated with inorganic suspended solids (peaking at 100 mg/L). Stowar (1997) found strong indications that macroinvertebrate communities 200 m downstream of the road crossing were affected by sediment from the crossing (levels of up to 100 mg/L had a marked impact), while a marginal degree of impact occurred 1000 m downstream, suggesting the effect is quite localised. Thus the threshold of ~30 NTU used in the Daly River and the 50 NTU threshold used in the Fitzroy are consistent with the above predictions.

Where diurnal dissolved oxygen (DO) was measured, turbidity was also logged using the Hydrolabs over the deployment period, in an effort to gauge the effect of cattle disturbance. This may prove a simple and useful addition to diurnal monitoring for streams subject to heavy cattle use and is discussed further in the results section 6.2.1.

Diurnal dissolved oxygen

The FARWH scoring bands for diurnal DO applied to both the Daly and Fitzroy river catchments are shown in Table 6.15. FARWH scores for reference and highly disturbed conditions were based exclusively on fish biota (tropical species from northern Australia), after Butler and Burrow’s (2007). This work defines a broad chronic ‘default’ trigger value at 30% saturation.

The establishment of a ‘low disturbance’ category was not favoured, given the uncertainties in translating laboratory-derived thresholds directly to field situations. Also, it is likely fish are adapted to low DO levels because levels of <75% are not unusual, and the adoption of a <75% chronic threshold would imply reference condition waters are in a chronic state, which is unlikely.

To calculate a diurnal DO FARWH score for each site, firstly the minimum mean DO (% saturation) was determined. Sites with a minimum above 30% saturation score 1. For any sites with a minimum of less than 30% saturation, every reading throughout the 24-hour monitoring period is assigned a binary score (1 or 0), depending if it is above 1, or below 0, on the 30% threshold. The time-weighted average of the binary scores was then calculated. This was the FARWH DO score for the site, reflecting the proportion of time spent above the 30% chronic threshold.

Table 6.15: Dissolved oxygen scoring for FARWH in both Daly and Fitzroy catchments.*

Minimum diurnal DO (% saturation)	Individual readings over 24 hrs	Binary score	FARWH score (time weighted)	Category
>30	-	1	1.00	Reference
<30	>30	1 or 0	Mean binary score (<1)	High disturbance

*** Two stages: 1) determine if the minimum diurnal DO is greater than 30 (score 1); 2) If minimum is below 30 determine the proportion of day spent below 30 = FARWH score (any value <1 = high disturbance).**

Butler and Burrows (2007) have extensively tested the DO thresholds for a range of tropical freshwater fish species. These included moderately sensitive (Barramundi *Lates calcarifer* and Gulf Saratoga *Scleropages jardinii*) to highly sensitive species (Banded grunter *Amniataba percoides* and fly-specked hardyhead *Craterocephalus stercusmuscarum*). Chronic (CTV) and acute (ATV) trigger values were subsequently derived for individual species together with a 'default' trigger value (Table 6.16).

Table 6.16: 'Default' acute and chronic guideline trigger values for freshwater habitats in northern Australia (Butler and Burrows 2007).

Indicator species	Water temperature (^{o}C)	Acute trigger value ATV) (% sat.)	Chronic trigger value (CTV) (% sat.)
Default	23–33	30	75

The default ATV has been defined for the most sensitive species, consequently less sensitive fish such as barramundi and Gulf Saratoga might still be found in waters with less than 30% (ATV) saturation. (See results section 6.2.1 for an example of this).

The ATV is close to the 2 mg/L ecological effects threshold prescribed by Wilcox (1998) for New Zealand freshwater systems (2 mg/L is equivalent to 23.3–27.8% saturation for a temperature range of 23–33 ^{o}C. This threshold also aligns with Connolly et al.'s study (2004) that found suppressed emergence of macroinvertebrates (sublethal effects) at 25–35% saturation (for lowland species) and 10–20% (for lowland and upland species).

Butler and Burrows (2007) recommend the minimum daily DO should be used to assess ANZECC guidelines for DO. It is important to note this requires DO data from at least one 24-hour monitoring period to assess the level of disturbance. Spot measurements are not useful and cannot be used (unless they were taken with certainty at the lowest point in the diurnal DO curve) (ANZECC 2000; Butler and Burrows 2007), though a dawn measurement would be a reasonable approximation.

The rationale for using percent saturation rather than mg/L is often not explicitly stated. Concentrations of dissolved oxygen vary with pressure and temperature leading to the possibility that sites with different temperatures, and thus DO concentrations (mg/L) could still both be at 100% saturation. In addition, a gradient in the percent saturation of oxygen determines oxygen transfer (Pusey per. comm.). However, reporting actual concentration (mg/L) establishes how much is available for biological reactions, so where possible both units of measurement should be used.

Nutrients

The FARWH scoring bands for nutrients in the Daly and Fitzroy river catchments are shown in Table 6.17 and 6.18 respectively. FARWH scoring bands for both catchments were derived from the 95th percentile of historical data (as close as possible to reference condition) where possible, in combination with local knowledge.

Table 6.17:Interim scoring bands for nutrients (µg/L) in the Daly River catchment.

Nutrient	Scoring band for river section	Sandstone country (upper reaches)	Lower Katherine and lower Douglas	All others	FARWH score	Category
NO3	95th percentile (x2, rounded)	10	400	200	1	Reference
	95th percentile (x5, rounded)	11–25	401–800	201–400	0.5	Low disturbance
	>95th percentile (x5, rounded)	>25	>800	>400	0.25	High disturbance
FRP	95th percentile (x2, rounded)	20	30	30	1	Reference
	95th percentile (x5, rounded)	21–40	31–60	31–60	0.5	Low disturbance
	>95th percentile (x5, rounded)	>40	>60	>60	0.25	High disturbance
TN	95th percentile (x2, rounded)	500	300	400	1	Reference
	95th percentile (x5, rounded)	501– 1200	301–800	401–900	0.5	Low disturbance
	>95th percentile (x5, rounded)	>1200	>800	>900	0.25	High disturbance
TP	95th percentile (x2, rounded)	60	30	40	1	Reference
	95th percentile (x5, rounded)	61–160	31–80	41–120	0.5	Low disturbance
	>95th percentile (x5, rounded)	>160	>80	>120	0.25	High disturbance

Table 6.18: Interim scoring bands for nutrients (µg/L) in the Fitzroy River catchment.

Nutrient	Scoring band for catchment	Fitzroy	FARWH score	Category
TN	95th percentile (x2, rounded)	600	1	Reference
	95th percentile (x5, rounded)	601–1500	0.5	Low disturbance
	>95th percentile (x5, rounded)	>1500	0.25	High disturbance
TP	95th percentile (x2, rounded)	50	1	Reference
	95th percentile (x5, rounded)	51–100	0.5	Low disturbance
	>95th percentile (x5, rounded)	>100	0.25	High disturbance

For the Daly River, nutrient concentrations are primarily determined by their groundwater source and are characteristically low in both nitrogen and phosphorus, with concentrations often near or below laboratory detection limits (Schult et al. 2007). Thus, no lower limits have been set for nutrients. The catchment has been divided into three broad categories for nutrient thresholds, influenced by the origin of the groundwater; Sandstone or Tindal limestone or other (i.e. river sections beyond the direct influence of the groundwater).

Schult et al. (2007) identified two reaches of high nitrate concentration, the lower Douglas River and the Katherine River downstream of the Katherine township. The high nitrate of the Douglas has its origins in the Tindal limestone aquifer and concentrations ranging from 56ug/L to 125ug/L have been reported (Schult et al. 2007; Townsend 2002). Though high nitrate concentrations are not characteristic of the Tindal aquifer and Douglas River, it may be a result of past agricultural practices and demonstrates the vulnerability of Tindal and other aquifers to nitrate contamination (Schult et al. 2007). High nitrogen concentrations in the Douglas River were not found to increase primary productivity, as the lower Douglas is known to be phosphorus limited (Schult et al. 2007). It does make it more susceptible to the addition of phosphorus, however, given the excess nitrogen. The source of high nitrate concentrations in the Katherine River is not known, but could originate from agricultural land use, seepage from Katherine township sewage ponds, or other sources.

In the Fitzroy River, sufficient historical data to derive 95th percentile thresholds was only available for total nitrogen and total phosphorus. ANZECC trigger values and Daly water quality thresholds are shown in Table 6.19. The only available data on thresholds for NO_x/NO_3 and FRP for the Fitzroy is provided in the ANZECC 2000 guidelines (Table 6.14). However, precaution should be used when applying ANZECC thresholds to the Fitzroy River as they were not developed using information from northern WA rivers. Calculating the FARWH scoring bands based on multiples of 95th percentiles resulted in higher thresholds than both Schult et al. (in the Daly) and the ANZECC guidelines trigger values. The exception was nitrate in the 'sandstone' river sections, which had a little more sensitivity than the ANZECC (lowland river) trigger value.

Table 6.19: Default ANZECCC trigger values and other water quality guidelines.

Source	Catchment reaches	Water quality parameter (µg/L)			
		NO_x/NO_3	FRP	TN	TP
ANZECCC default guidelines (Tropical Australia 2000)	Upland River	30	5	150	10
	Lowland River	10	4	200-300	10
Schult et al. (2007)	Daly River (middle reaches)	<1	9	110	9
FARWH	Sandstone origin	>10	>20	>500	60
	Tindal limestone origin (lower Katherine and Douglas)	>400	>30	>30	>30
	Other	>200	>30	>400	>40
	Fitzroy	-	-	>600	>50

The ecological significance of nutrient concentrations lies in their limitation of the growth of primary producers, notably benthic algae and phytoplankton. In the Daly catchment, a study was undertaken to evaluate nutrient limitation, using nutrient-infused agar blocks, using the method of Cardinale (2009), and determination of algal biomass based on chlorophyll-a. At the 22 sites tested for nutrient limitation, four were P limited and five N nitrogen limited, while the rest did not vary significantly from the control indicating N and P co-limitation. This range of responses concurs with the results of Townsend et al. (2008) for *Spirogyra* in the Daly and Douglas rivers, while Robson et al. (2008) reported co-limitation for benthic algae and phytoplankton in the middle reaches of the Daly River. The results emphasise that no single nutrient limits benthic algal biomass. Therefore knowledge of the nature of nutrient limitation is required to evaluate the significance of nutrient concentrations and inform a FARWH water quality attribute score.

Step 3—Aggregation

The lowest FARWH score of all measured water-quality parameters was used in the calculation of the final FARWH water quality theme score. This rule acknowledges that the implied ecological degradation of any one attribute will not be compensated by an attribute that has a value that falls within the natural range. For example, if pH was 3, then the stream water quality is considered degraded, regardless of the nutrient or DO concentrations, turbidity or conductivity.

In the Daly and Fitzroy rivers, each FARWH reach was represented by a single site; the site score therefore was the same as the reach score. The Daly catchment was divided into two strata; developed zone and undeveloped zone. Thus two separate scores were derived for each of these strata. Within each of these zones, reach scores were averaged for stream order and weighted for contributing length of the total stream network within that zone (Equation 6.1 developed zone and Equation 6.2 undeveloped zone). The Fitzroy River catchment was calculated using the same single equation (Equation 6.1) but for the entire SWMA (i.e. weighted for the total stream network of the catchment).

To compute the final water quality theme score for the Daly River SWMA, the stratified zone scores are weighted by contributing stream length to the total SWMA perennial network: developed zone = 747 km (47%) of perennial streams; undeveloped zone = 840 km (53%) of perennial streams (Equation 6.3).

Equation 6.10

$$WQ_d = ((L_{S1} / L_{SN} * S_{A1}) + (L_{S2} / L_{SN} * S_{A2}) + (L_{S3} / L_{SN} * S_{A3}) + \ldots)$$

where:
WQ_d = *final FARWH water quality theme score for developed strata (0-1)*
L_{S1} = *combined length of all 1st order streams in developed strata (L_{S2} = 2nd order streams etc.)*
L_{SN} = *total length of entire stream network in developed strata*
S_{A1} = *average score for 1st order streams in developed strata (L_{S2} = 2nd order streams etc.).*

Equation 6.2

$$WQ_u = ((L_{S1} / L_{SN} * S_{A1}) + (L_{S2} / L_{SN} * S_{A2}) + (L_{S3} / L_{SN} * S_{A3}) + \ldots)$$

where:
WQ_u = *final FARWH water quality theme score for undeveloped strata (0–1)*
L_{S1} = *combined length of all 1st order streams in undeveloped strata (L_{S2} = 2nd order streams etc.)*
L_{SN} = *total length of entire stream network in undeveloped strata*
S_{A1} = *average score for 1st order streams in undeveloped strata (L_{S2} = 2nd order streams etc.).*

Equation 6.3

$$WQ = (W_d * 0.47) + (W_u * 0.53)$$

where:
WQ = *final FARWH water quality theme score for the Daly River SWMA (0–1)*
WQ_d = *final FARWH water quality theme score for developed strata (0–1)*
WQ_u = *final FARWH water quality theme score for undeveloped strata (0–1).*

6.3 Results

6.3.1 Results for Daly River catchment

The range of values for each metric is shown in Table 6.20, with mean (median pH) results for each site shown in Table 6.21. For sites scoring less than 1, a summary of all attribute mean values (median pH) and their FARWH scores is given in Table 6.22.

Green Ant, Green Ant tributary and Station site reaches were located outside of the river sections used to define reference conditions and scoring bands. These reaches lacked historical data, and were considered test sites because of the intensity of grazing in the catchments. These sites were compared against the Daly upper river section (prior to confluence with the Douglas River) because they are supplied by the same groundwater system. Four sites fell within likely ‘transition zones’ (DP-01, FP-01, GA-01, ME-01), where water quality is likely to be so variable as to make it difficult to compare against the scoring bands and with the Daly upper bands. None registered any high-scoring metric. In the future, however, it would be best to sample outside these zones.

Table 6.20: Range of values from all 41 FARWH sites sampled in the Daly catchment (median pH, mean conductivity, turbidity and nutrients (TN, TP, NO_x, PO_4).

	pH	Conductivity	Turbidity	TN (µg/L)	TP (µg/L)	NO_x (µg/L)	PO_4 (µg/L)
Max.	8.38	1328.0	44.07	1905	32	1640	10
Min.	6.58	14.0	0.56	25	2	0.5	1
FARWH reference (range of all river sections combined	4.5–7.5; 7–8.5	100–2600*	10–20*	0.4–0.5*	0.03–0.06*	0.01–0.4*	0.02–0.03*

* range specifies variation between river sections, not a lower limit.

Conductivity

The average conductivities of all sampled reaches were within reference condition. Four sites (DP-01, FP-01, GA-01 and ME-01) were located in the 'transition zone' and were therefore assessed against the Daly upper river section scoring bands.

pH

The median pH of all sampled reaches was within reference conditions, except for ST-03. The pH at this site was 8.03 and outside the 'sandstone' river section reference condition (upper limit of pH 7.5). This may be due to high rates of primary production (dissolved oxygen was 93% (7.53 mg/L) at 5.30pm), though it is more likely that the reference condition is applicable to this site, and needs to be confirmed by ionic chemical analyses.

The reach with the lowest pH had low conductivity levels, as expected for reference or undisturbed condition.

Table 6.21: Mean (turbidity, conductivity and nutrients) and median (pH) values of attributes measured at 41 FARWH sites in the Daly catchment. (Soluble molar N: P ratio also included).

Site	pH	Conductivity	Turbidity	TN	TP	NO_x-N	PO_4_P	min DO	Soluble molar N:P
		µS/cm	NTU	µg/L	µg/L	µg/L	µg/L	% sat	
DG-01	7.36	219	3.1	120	3	89	3	81	65.69
DG-02	6.98	17	5.2	79	9	1	3	87	0.44
DP-01	7.92	540	3.8	137	6	1	5	66	0.44
DY-01	8.32	531	4.0	93	5	23	4	-	12.73
DY-02	7.82	638	3.3	25	4	1	4	-	0.28
DY-03	8.08	628	4.7	43	4	8	5	-	3.54
DY-04	8.07	581	6.7	48	4	1	7	-	0.26
ED-01	7.49	16	2.7	56	2	2	4	84	1.11
FL-01	7.55	886	2.3	33	4	2	4	-	1.11
FL-02	7.77	749	1.4	60	5	1	6	-	0.18
FP-01	8.38	303	7.3	156	7	1	5	59	0.33
GA-01	7.42	460	3.2	182	10	19	4	65	9.71
GA-02	7.97	473	2.3	43	6	1	6	79	0.18
GA-03	7.68	615	3.4	148	7	106	6	74	38.97
GA-04	8.00	548	2.2	105	18	6	6	69	2.07
GA-05	8.05	555	2.5	162	17	5	7	76	1.53
GT-01	7.00	195	7.9	139	18	1	7	72	0.32
GT-02	7.43	589	4.5	141	7	7	5	17	3.10
GT-03	8.01	620	2.9	206	7	98	5	68	48.22
GT-04	7.76	620	5.4	1905	14	1640	6	38	660.26
HY-01	7.93	570	2.6	51	3	4	5	-	1.77
HY-02	7.95	606	1.9	61	5	2	6	68	0.81
KA-01	7.90	520	3.2	87	4	85	3	-	62.74
KA-02	7.29	496	4.0	151	4	113	4	-	62.55
KA-03	7.00	33	2.6	76	7	1	5	-	0.22
KA-04	7.08	14	4.0	71	4	2	3	86	1.48
KA-05	6.58	21	0.6	63	4	3	1	82	6.64
KA-06	7.20	38	2.1	158	10	2	5	85	0.89
KG-01	7.36	49	6.1	146	12	3	7	-	0.95
MD-01	7.84	614	3.2	87	7	1	5	49	0.63
ME-01	7.40	124	1.4	125	6	2	10	-	0.44
SC-01	8.07	1328	2.4	106	5	2	5	-	0.89
SM-01	7.01	19	2.3	43	2	1	1	91	1.11
SN-01	8.23	502	4.8	88	4	2	6	88	0.76
SN-02	7.92	585	2.1	86	2	18	5	81	8.27
SN-03	8.07	541	44.1	840	32	43	5	-	19.13
SN-04	7.46	484	5.1	374	5	254	6	32	93.74
SN-05	8.04	573	4.6	1338	7	18	6	64	6.74
ST-01	8.00	556	1.7	83	3	147	5	92	65.25
ST-02	8.10	599	5.8	47	2	6	5	90	2.66
ST-03	8.03	97	1.8	40	5	1	4	-	0.28

Table 6.22: Daly River catchment sites with FARWH scores <1. Score for each attribute and final score for the site (= score of poorest attribute score).

Site	pH		Conductivity (µS/cm)		Turbidity (NTU)		TN (µg/L)		TP (µg/L)	
	Site median	FARWH score	Site mean	FARWH score	Site mean	FARWH score	Site mean	FARWH score	Site mean	FARWH score
GT-02	7.43	1.00	589	1.00	4.51	1.00	141	1.00	7	1.00
GT-04	7.76	1.00	620	1.00	5.4	1.00	1905	0.25	14	1.00
SN-03	8.07	1.00	541	1.00	44.1	0.25	840	0.50	32	0.50
SN-04	7.46	1.00	484	1.00	5.06	1.00	374	1.00	5	1.00
ST-03	8.03	0.50	97	1.00	1.78	1.00	40	1.00	5	1.00

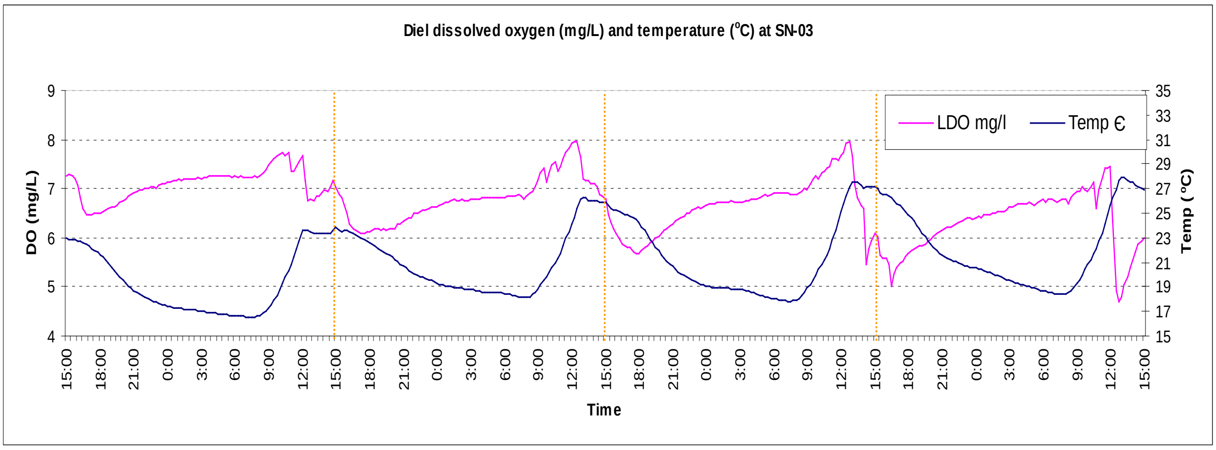
Site	NOx (µg/L)		PO4 (µg/L)		DO min diurnal (% sat)		FINAL FARWH score	Lowest scoring attribute
	Site median	FARWH score	Site mean	FARWH score	Site min	FARWH score		
GT-02	7	1.00	5	1.00	16.8	0.00	0.00	DO
GT-04	1640	0.25	6	1.00	37.6	1.00	0.25	NOx, TN
SN-03	43	1.00	5	1.00		-	0.25	Turbidity
SN-04	254	0.50	6	1.00	31.7	1.00	0.50	NOx
ST-03	1	1.00	4	1.00		-	0.50	pH

Water clarity

Average turbidity was within reference conditions for most sites, except for SN-03, where the average was skewed by one extremely high reading of 171 NTU in June. In combination with high total nutrients, the spot measurements at this site are indicative of cattle disturbance.

In addition, the turbidity and dissolved oxygen data logged over the course of several days showed dissolved oxygen levels decreased in response to plumes of high turbidity (Figure 6.5). The timing appears to coincide with when cattle accessed the water's edge to drink and, given the site is known to be heavily impacted by cattle (both in the riparian zone and entering the stream), it provides an indication of the impact on water quality resulting from heavy cattle use (Figure 6.6). This example highlights the value of diurnal monitoring and the limited use of spot measurements.

Figure 6.5: Effect of turbidity on diurnal dissolved oxygen cycle at Station Creek site SN-03.



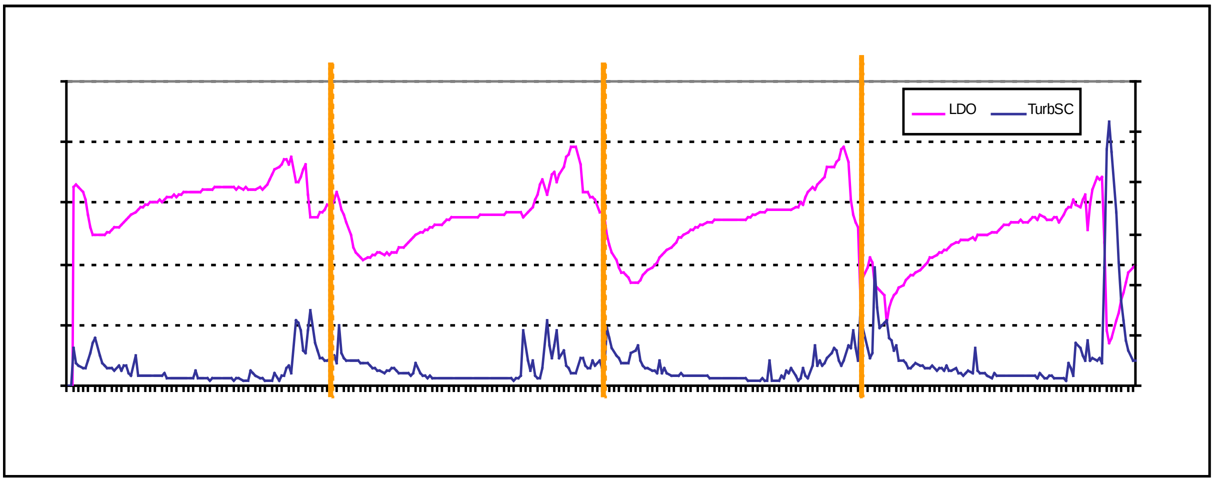


Figure 6.6: Station Creek site SN-03 (left) and evidence of cattle crossing upstream (right).

Diurnal dissolved oxygen

Diurnal DO was assessed at 26 sites. Only one reach/site, GT-02 (10 July 2009) was found to be below reference condition. With a minimum value of 16.8% saturation its entire diurnal cycle was below the 30% mean threshold, giving it a score of 0.

It is important to note this did not necessarily prevent any fish from occupying the site. The FARWH fish survey carried out at GT-02 (20 July 2009) counted 186 individuals of six species (*Ambassis sp*. (11), *Craterocephalus stramineus* (3), *Leiopotherapon unicolour* (22), *Melanotaenia australis* (51), *Morgurnda morgurnda* (98), *Neosilurus hyrtlii* (1)). The spot-measured DO concentration on the day was 22.5% saturation (2.07mg/L). Unfortunately, diurnal DO for the 24-hour period immediately before the fish survey was not collected. Therefore we were unable to confirm if the DO levels before the survey were consistent with that measured on 10 July.

In all other water quality metrics GT-02 was ‘undisturbed’. Site GT-02 is shown in Figure 6.7.

Figure 6.7: GT-02 site photos.

Interestingly, GT-04 (Figure 6.8) and SN-04 (Figure 6.9) were very close to the threshold of disturbance (37.6% saturation, 31.7 % minimum saturation respectively). While these sites were not picked up as ‘disturbed’ by the DO metric, both of them sites scored less than 1 for nutrient indices, and so a level of disturbance was still identified for the site.

Figure 6.8: GT-04 site photos (top), evidence of pig wallows upstream (bottom left).

Figure 6.9: SN-04 site photo (left) and evidence of cattle entering the stream (right).

Nutrients

Excess nitrogen was detected at SN-04 (nitrate) and GT-03 (both total nitrogen and nitrate) (Figure 6.9, Figure 6.10 respectively). SN-03 was in excess of both total nutrients and, in combination with high turbidity, this suggests that there is cattle-generated disturbance at this site.

Figure 6.6: GT-03 site photos and evidence of cattle impacts.

There were four other sites (GT-01, GT-03, SN-01 and SN-03) where cattle disturbance may be expected to affect water quality.

Final FARWH scoring for the Daly River catchment

The FARWH water quality theme score for the Daly River catchment undeveloped zone is 1, while for the developed zone it is 0.91 (Table 6.23). The lower score developed zone appears to reflect the different level of disturbance between the strata. All reaches scoring less than 1 were found to be first-order streams within the developed agricultural zone. The integrated Daly River SWMA score is 0.96.

The final FARWH score for Darwin Harbour was 0.89, affected primarily by the nitrate (first-, third- and fourth-order streams) and phosphate (third-order streams) attributes. This is very close to the score of 0.91 in the developed zone of the Daly River catchment.

Table 6.23: Stream-order scores and final calculation of the FARWH water quality theme for a) developed agricultural zone and (b) undeveloped zone in the Daly River catchment. Final scores use stream-order length weighted scores. Scores are between 0–1.

(a) Developed Zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	Number of sample reaches	(A) Average score	Zone-weighted score (W*A)
1st	243 (32%)	0.32	26	12	0.73	0.23
2nd	184 (25%)	0.25	21	11	1.00	0.25
3rd	127 (17%)	0.17	16	4	1.00	0.17
4th	68 (9%)	0.09	6	2	1.00	0.09
5th	125 (17%)	0.17	7	2	1.00	0.17
Total	**747 km**		**76**	**32(42%)**		**0.91**

(b) Undeveloped zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	Number of sample reaches	(A) Average score	Zone-weighted score (W*A)
1st	258 (31%)	0.31	17	2	1.00	0.31
2nd	195 (23%)	0.23	17	2	1.00	0.23
3rd	209 (25%)	0.25	24	2	1.00	0.25
4th	52 (6%)	0.06	4	1	1.00	0.06
5th	126 (15%)	0.15	11	2	1.00	0.15
Total	**840 km**		**73**	**9 (12%)**		**1.0**

Table 6.24: Aggregation of water quality theme scores for the Daly River SWMA.*

SWMA	Zone score (z)	Weighting (w)	(w * z)
Developed zone	0.91	0.47	0.43
Undeveloped zone	1.0	0.53	0.53
Daly River SWMA			**0.96**

***The developed and undeveloped zone scores are weighted for contributing length of perennial streams to the total SWMA perennial network (Eq. 3). Scores are between 0–1.**

6.3.2 Results for Fitzroy River catchment

Water quality was measured and recorded at 34 sites geographically spread across the three Fitzroy River subregions. Ten sites were located on small tributaries. 13 were sampled from the middle region and five from the upper catchment. Sites were restricted to areas of the catchment that had surface water present during the dry season and were disproportionally spread across the six stream orders.

Scores for each of the water quality metrics were calculated using the scoring bands developed in section 6.1.3. The range of values recorded for each metric and the reference condition (section 6.1.4) for each metric is shown in Table 6.25.

Table 6.25: Range of values from all 34 FARWH sites sampled in the Fitzroy catchment, for pH, conductivity, turbidity and nutrients (total P and total N).

Parameter	Conductivity (µS/cm)	pH	Turbidity (NTU)	Nutrients	
				Total N (µg/L)	Total P (µg/L)
Max.	1119	9.84	62.2	-	85
Min.	101	7.65	0.1	-	19
FARWH reference level	<2800 (<900 upper tributaries)	7.5–9.0	<20	600	<50

A comparison of water quality measurements revealed that the precautionary FARWH bands for reference level are exceeded by the following water quality measures; turbidity, pH, total P and total N. While all conductivity measurements fell within the reference level, between one and seven sites exceeded reference bands for the remaining water quality parameters (Table 6.26). As a result of the limited data, and hence the uncertainty surrounding the water quality bands in the Fitzroy River, the current field trial serves to help ground-truth the precautionary bands that were developed in section 6.1. Recommendations and patterns in water quality parameters are discussed for each of these parameters in the following section.

Conductivity

All sites sampled were within the reference condition range for conductivity. Although information from literature reviews and analysis of historical data provided evidence of a variation in conductivity levels between the upper tributaries and the rest of the catchment, analysis, and comparison of field recordings for salinity revealed inconsistencies with this pattern. For example, the reference site for upper tributaries recorded a salinity value double that for reference sites in the mid and upper regions. These discrepancies highlight the difficulties and the levels of certainty in determining informative scoring bands when there is limited historical data and regional knowledge on the natural variation across a SWMA, particularly in a large SWMA such as the Fitzroy.

Table 6.26: Values of attributes measured at 34 FARWH sites in the Fitzroy catchment.

Site	Region	Stream order	Conductivity	Turbidity	TN	TP	pH	Min. DO
			µS/cm	NTU	mg/L	mg/L	pH units	% sat
FARWH_34	S	1	1068	22.1	0.46	0.033	9.03	-
FARWH_24	S	1	737	2.3	0.06	0.035	7.65	33.2
FARWH_10	S	1	112	4.6	0.60	0.047	9.84	52.6
FARWH_3	S	1	344	7.7	0.10	0.029	8.84	99.5
FARWH_33	S	2	141	9.5	0.66	0.041	8.41	22.3
FARWH_28	S	2	898	17.2	0.39	0.047	8.82	42.3
*FARWH_30	S	3	762	1.8	0.10	0.032	8.71	43.7
FARWH_32	S	3	101	28.6	0.77	0.057	8.8	94.5
FARWH_17	M	4	386	7.0	0.23	0.051	-	43.5
FARWH_31	S	4	181	0.1	0.39	0.03	8.56	33.3
FARWH_20	U	4	314	56.0	0.78	0.085	-	38.2
FARWH_21	U	4	253	22.0	0.43	0.044	-	59.3
FARWH_6	M	5	412	62.2	0.13	0.062	8.6	-
*FARWH_8	M*	5	304	8.3	0.16	0.053	8.21	-
FARWH_7	M	5	223	6.8	0.24	0.026	9.17	-
FARWH_26	U	5	300	1.2	0.21	0.019	9.38	-
*FARWH_27	U	5	274	0.8	0.23	0.024	8.68	-
FARWH_29	U	5	400	1.6	0.18	0.02	8.96	-
FARWH_25	U	5	182	1.3	0.21	0.024	9.31	54.7
FARWH_13	M	6	316	11.2	0.16	0.052	8.76	48.4
FARWH_11	M	6	1098	6.9	0.09	0.049	8.56	-
FARWH_4	M	6	356	3.8	0.09	0.049	8.97	40.5
FARWH_9	M	6	1119	7.6	0.09	0.054	8.74	75.0
FARWH_22	M	6	1037	-	0.12	0.040	8.08	-
FARWH_2	M	6	329	3	0.09	0.048	9.04	-
FARWH_12	M	6	390	11.4	0.14	0.053	8.80	49.1
FARWH_5	M	6	354.8	7.4	0.08	0.050	8.94	80.0
FARWH_1	M	6	335.7	3.6	0.1	0.049	8.96	-

* reference site

pH

Of the eight sites, 24% recorded a pH range outside of the reference condition. Although high levels of pH are often associated with high levels of productivity, there have been no other studies with similar pH recordings in the Fitzroy River catchment (R Doble unpublished data). As little knowledge of either the natural variation of pH within the catchment or the ecological implications of the pH bands was available, it was decided to remove pH from the scoring for the Fitzroy. Only with an increased knowledge of the natural variations in the catchment, and the implications for high levels of pH on the ecological health of the river, can the inclusion of pH, or the resetting of the upper band limit, be supported.

Turbidity and nutrients

Elevated levels of turbidity were generally associated with increased levels of nutrients recorded at the site (either total P or total N). In combination with high total nutrients, these spot measurements can be indicative of a cattle disturbance. Investigations into whether turbidity and nutrients exhibit a response to a cattle disturbance gradient are provided in Chapter 11.

Dissolved oxygen

Data loggers recorded diurnal DO concentrations at 14 sites across the Fitzroy River catchment. Only one reach/site (FARWH_33), recorded DO outside of reference condition, with levels falling briefly below the 30% mean threshold (Table 6.26). This site recorded a minimum value of 22.3% and was recorded below 30% for five of the 24 hours. It scored 0.78, with all other sites for this metric scoring a value of 1.

Final FARWH scoring for the Fitzroy River catchment

Twelve sites recorded water quality parameter scores of less than 1 (Table 6.27). Of these sites, the lowest attribute was taken as the final water quality score for that site (Table 6.27).

Table 6.27: Fitzroy River catchment sites with FARWH scores <1. Score for each attribute and final score for the site (= score of poorest attribute score).

Site	Turbidity		TN		TP		DO min diurnal		FINAL FARWH score	Lowest scoring attribute
	NTU	FARWH score	mg/L	FARWH score	mg/L	FARWH score	% sat	FARWH score		
34	22.1	0.50	0.46	1.00	0.033	1.00	-	-	0.50	Turbidity
10	4.6	1.00	0.60	0.50	0.047	1.00	52.6	1.00	0.50	TN
33	9.5	1.00	0.66	0.50	0.041	1.00	22.3	0.78	0.50	TN
32	28.6	0.50	0.77	0.50	0.057	0.50	94.5	1.00	0.50	Turbidity, TN, TP
17	7.0	1.00	0.23	1.00	0.051	0.50	43.5	1.00	0.50	TP
20	56	0.25	0.78	0.50	0.085	0.50	38.2	1.00	0.25	Turbidity
21	22	0.50	0.43	1.00	0.044	1.00	59.3	1.00	0.50	Turbidity
6	62.2	0.25	0.13	1.00	0.062	0.50	-	-	0.25	Turbidity
8	8.3	1.00	0.16	1.00	0.053	0.50	-	-	0.50	TP
13	11.2	1.00	0.16	1.00	0.052	0.50	48.4	1.00	0.50	TP
9	7.6	1.00	0.09	1.00	0.054	0.50	75.0	1.00	0.50	TP
12	11.4	1.00	0.14	1.00	0.053	0.50	49.1	1.00	0.50	TP

Scores for each stream order were averaged and weighted using Equation 6.1 to produce a Fitzroy River SWMA water quality score of **0.78**. This was similar to the Ord River catchment water quality theme score of **0.74**.

Table 6.27: Computation of the FARWH water quality y subindex for the Fitzroy SWMA.*

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Stream order length weighted score (W*A)
1st	5904 (50%)	0.50	600	4	0.69	0.34
2nd	2813 (24%)	0.24	261	2	0.75	0.18
3rd	1872 (16%)	0.16	201	2	0.75	0.11
4th	632 (5%)	0.05	71	4	0.56	0.03
5th	225 (2%)	0.02	23	7	0.61	0.01
6th	454 (4%)	0.04	35	9	0.77	0.03
Total SWMA	**11900 km**	**1**	**1191**	**28 (2.4%)**		**0.71**

*** Final scores are the sum of stream order length weighted scores. Scores are between 0–1.**

6.4 Discussion

The application of the FARWH water quality theme to the wet/dry tropical catchments of the Daly and Fitzroy rivers was constrained by the lack of reference data, limited knowledge about the ecological response to changes in water quality attributes and the use of a limited number of spot measurements.

In both catchments, reference water quality data originated from short-term (generally 1 year or single season) sampling conducted for a specific project. This data, while designed to meet specific project aims, has nevertheless proved valuable in informing this project of reference condition. Not surprisingly though, water quality data is not available throughout the catchments, but tends to be concentrated spatially and temporally leaving some rivers poorly, if at all, represented in the reference data sets. There is a bias for water quality data to be collected for high-order rivers. This is significant, because it is the lower order (smaller) rivers and streams that are most vulnerable to cattle and other impacts. Available water quality data is also heavily biased to dry season data; in general wet season water quality data is scarce. Data used in creating reference bands was deliberately limited to that taken during the dry season.

Based on the review of available historical data, there are several other issues worth noting. Firstly, analysis of historical data is time consuming. Simple tasks such as identifying the location of sites and analytical methods used are not always clear from the original data. Additionally, the metrics (e.g. filterable reactive phosphorus versus soluble phosphorus) and detection limits often differ between the primary data sets.

The collation exercise has highlighted the value of long-term data collection from a site at a specific time of year, supported by ancillary information, such as discharge, to provide context and permit evaluation of long-term trends. This was absent in the historical records for both Daly and Fitzroy river catchments.

Despite these constraints, a reasonable result has been achieved in describing reference condition for most of the Daly River catchment during the dry season. This is primarily because the dry season flows are supplied principally by two groundwater systems with distinct chemical signatures, though in-stream processes will modify nutrient concentrations. Limited knowledge of the natural variability in water quality makes it difficult to define reference conditions in the Fitzroy River catchment.

Reference condition was selected largely on land use, and can be best termed ‘least disturbed,’ as described by Stoddard et al. (2006). Both catchments had less than 7.5% land cleared, though it is feral animals and cattle that are more likely to have an impact on water quality than cleared land. Feral animals, on the whole, may cause negligible impact, but on occasions can have significant impact, for example, pigs foraging in river shallows.

The second constraint to applying the FARWH water quality theme is the lack of knowledge about the ecological impact of pollution on river health. In the wet/dry tropics, for the most part, there is not a large range of disturbed water quality sites to permit an evaluation of impact. This contrasts with temperate Australia, where highly polluted rivers provide an insight into impact and provide a means to assess ecological significance. To do this in the wet/dry tropics, experiments may need to be undertaken, except in the case of mine pollution. The bands chosen for the water quality metrics are based mainly on expert knowledge, supported though by some literature, but could not be described as being ‘proven’.

Water quality data has been based on grab samples, with the exception of dissolved oxygen, where diurnal measurements were made. For cattle and feral animal impacts, water quality pollution occurs as a plume of ‘polluted’ water that travels downstream following animal disturbance. These events are temporary and are unlikely to be sampled due to their relatively short duration. This may mean such events are not significant; for example, a high turbidity plume may limit photosynthesis for a short time only. However, such an argument could not be so readily stated for a plume of nutrients, which could be taken up by stream benthic algae to increase biomass. This sampling, therefore, poses some practical challenges.

In conclusion, the water quality index appears to provide reasonable results. However, the approach used here relies heavily on expert opinion, given the extensive knowledge gaps. As such, significant improvements to the scoring bands and reference ranges could be made in future assessments. These modifications should be addressed in the future when more water quality data becomes available.

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7 Physical form theme

7.1 Introduction

The physical form theme consists of two subindices: 1) bank stability (bank erosion) and 2) connectivity (longitudinal connectivity of surface water). Two additional subindices suggested by NWC (2007) were rejected for inclusion in the wet/dry tropical FARWH. Bedload characterisation was excluded as no suitable reference condition could be determined, and large wood (removal of in-stream debris) was excluded because of its low abundance in northern rivers. This chapter aims to calculate the bank stability and connectivity subindices and identify challenges in their application.

7.2 Methods

7.2.1 Bank stability

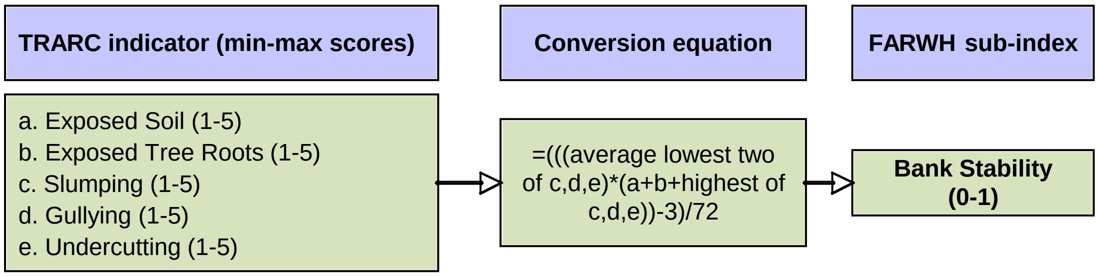
The bank stability subindex is an assessment of erosion to the stream banks. Bank stability was assessed using field measurements of soil, exposed tree roots, slumping, gullying and undercutting, following the TRARC approach (Dixon et al. 2006). TRARC uses a standard 100 m transect running parallel to the stream. In these trials, up to four transects were placed over a distance of 250 m (two on each bank, 50 m apart). The exception was on larger rivers, when crossing to the opposite bank was not possible. In such cases two transects were placed on one bank only. TRARC field procedures followed those described in Dixon et al. (2006).

Data analysis

Earlier trials of converting TRARC to the FARWH bank stability subindex weighted each of the five TRARC erosion metrics equally (see desktop trials, Dixon et al. 2009). However, field observations revealed that all five erosion features rarely occurred simultaneously (e.g. a bank could be severely slumped but still have minimal exposed tree roots and no gullying). Consequently, equal weighting of erosion metrics failed to adequately represent the full linear range from 0 to 1. To address this limitation, an improved integration process was developed during the field trials described here. Scenario testing of various integration methods were explored (see Appendix 13.6). The resulting approach represents a more realistic spread of possible scores between 0–1, where 0 = complete bank degradation and 1 = natural bank features.

For the field trials presented here, a modified ‘inverse ranking’ method was adopted to integrate the five erosion metrics: the **average of the two lowest** scoring erosion metrics of either 1) slumping, 2) gullying or 3) undercutting are **multiplied** by the **sum of the remaining** metrics (Figure 7.18). In this approach, greater weighting is applied to slumping, gullying and undercutting as these erosion features have greater spatial impact and represent the majority of bank degradation in the wet/dry tropics.

Figure 7.18: Conversion process of TRARC scores into FARWH bank stability score. Scores are range



standardised to 0-1.

Following conversion of the TRARC erosion scores to the FARWH bank stability scores, reference sites were selected to represent each stream order in the Daly River catchment (see criteria in Chapter 8, 'Fringing zone theme') and region in the Fitzroy River catchment (see criteria in Chapter 3.4.2, 'Reference condition'). Reference sites were identical to those of the fringing zone theme as these sites were seen to have relatively intact banks and minimal pressures (e.g. land clearing, fire and cattle). Reference sites were selected to represent each stream order (for the Daly River catchment) or region (for the Fitzroy River catchment).

For each stream order or region, reference site scores were averaged to produce an 'expected' bank stability score. Test site scores (i.e. 'observed' (O) scores) were compared to the 'expected' (E) reference scores, resulting in an O/E score for the subindex. Because of our poor understanding of the natural variability of bank erosion at reference sites, we decided to cap O/E scores that exceeded 1.0—i.e. test sites with less erosion than reference sites (O/E>1.0) were capped at 1.0 and not scaled lower to reflect any difference from 'expected'. Scores are optionally grouped into descriptive bands to aid interpretation: largely unmodified (1.0–0.8), slightly modified (0.8–0.6), moderately modified (0.6–0.4), substantially modified (0.4–0.2) and severely modified (0.2–0).

Integration and aggregation

Sites within the same reach were averaged to give a reach score (not required for this study because selected reaches were represented by only one site). Reach O/E scores were then averaged for each stream order and weighted for contributing length of total stream network to produce a bank stability subindex score (Equation 7.11).

Equation 7.11

$$BS = ((L_{S1} / L_{SN} * BS_{S1}) + (L_{S2} / L_{SN} * BS_{S2}) + \ldots)$$

where:

BS = *bank stability subindex score for the SWMA/zone (0–1)*
L_{S1} = *combined length of all 1^st^ order streams* (L_{S2} = *2^nd^ order etc.)*
L_{SN} = *total length of entire stream network*
BS_{S1} = *average bank stability score for 1^st^ order streams* (BS_{S2} = *2^nd^ order, etc.).*

7.2.2 Connectivity

This is an assessment of how human-built structures have impeded the longitudinal connectivity of habitats for aquatic biota. Barriers may restrict the upstream movement of fish and turtles and the downstream drift of invertebrate larvae. They may also alter the timing and frequency of flooding events that would naturally extend onto the floodplain. This subindex does not attempt to evaluate lateral connectivity.

Limited information was available on the number and location of small structures such as causeways, culverts, weirs and other crossings in each SWMA. Field reconnaissance of road–stream intersections concluded that mapped data (topographical maps) of road crossings was inadequate for identifying the number and variety of crossings. Observations of many small structures during the field surveys, however, suggested that most would not represent significant barriers to the movement and dispersal of aquatic biota during periods of river flow.

Only large dams, weirs and causeways were deemed appropriate for the assessment of connectivity in both the Daly and Fitzroy River catchments. It should be noted that, although some weirs act as barriers to fish movement during low flows, the impact of these structures might be negligible during wet season floods. Consequently, this assessment targeted dry season flows and obvious barriers to movement of aquatic biota, especially upstream movement of fish.

Connectivity scores for each reach were calculated following a modified method described by NWC (2007). Human-built structures were assigned a weighting based on the type of physical barrier (e.g. dam, weir or causeway) and a second weighting for the duration of time that each barrier restricted the movement of aquatic biota (e.g. dry season only, or entire year). The final connectivity weighting represented the product of the two (Table 7.33). These weightings were derived from those suggested in NWC (2007) and by expert opinion.

Table 7.33: Connectivity weightings for (a) type of barrier and (b) seasonal impact. *

Barrier type	(a) Weighting	Seasonal impact	(b) Weighting
Major barrier (dams & weirs >1 m)	1	Barrier all year	1
Moderate barrier (weirs <1 m)	0.5	Barrier dry season	0.5
Minor barrier (causeways)	0.25	Barrier rarely	0
Negligible barrier (small weirs & wet crossings)	0	-	-
Final connectivity weighting (w_c) = a * b			

*** Consideration of upstream movement of fish was the primary basis for these weightings. A final connectivity weighting is the product of (a) and (b).**

Reaches within 40 km upstream and 40 km downstream of structures were scored against the connectivity weighting. Reaches were assigned an additional weighting dependent on their distance from a barrier, with reaches down-weighted in relation to remoteness from a barrier (Equation 7.12). Tributaries within 40 km were also scored against the barrier. Reaches further than 40 km from a barrier assigned a score of 1.0. In the event that a reach was proximal to multiple barriers, the lowest score was assigned to that reach.

Equation 7.12

$$Con_R = 1 - (w_c/n)$$

where:
Con_R = *connectivity reach score (0–1)*
w_c = *connectivity weighting (from Table 7.33)*
n = *reach number in relation to proximity to barrier (e.g. n=1 for reach with barrier n=2 for next upstream or downstream reach from barrier etc; capped at 40 km)*

Aggregation of connectivity scores

Connectivity scores were calculated for every reach in the SWMA/zone. Reach scores were aggregated to the SWMA/zone-scale by weighting their contribution to stream length in the entire stream network (Equation 7.13).

Equation 7.13

$$Con = ((L_{R1} / L_{SN} * Con_{R1}) + (L_{R2} / L_{SN} * Con_{R2}) + \ldots)$$

where:
Con = *connectivity subindex score for the SWMA/zone (0–1)*
L_{R1} = *length of reach 1 (L_{R2} = reach 2, etc.)*
L_{SN} = *total length of entire stream network*
Con_{R1} = *connectivity reach score for reach 1 (Con_{R2} = reach 2 etc.) (from Equation 7.12);*

7.2.3 Integration of scores to a pPhysical form theme score

For the Daly River SWMA, where scores have been aggregated to a stratified zone (developed and undeveloped), an additional integration step was used to compute each subindex and final physical form theme score. For each subindex (bank stability and connectivity), zone scores are weighted by contributing stream length to the total SWMA perennial network: Developed zone = 747 km (47%) of perennial streams; undeveloped zone = 840 km (53%) of perennial streams (Equation 4.8).

Equation 7.14

$$SI = (SI_D * 0.47) + (SI_U * 0.53)$$

where:
SI = *subindex score for the Daly River SWMA (0–1)*
SI_D = *subindex score for the Daly River developed zone (0–1)*
SI_U = *subindex score for the Daly River undeveloped zone (0–1).*

Integration of bank stability and connectivity subindices into a final physical form theme score for the SWMA or stratified zone follows Equation 7.15. Bank stability was given a higher weighting (80%) than connectivity (20%), as erosion is more likely to vary in the future than the number of large dams or weirs in the catchment. Thus, it provides a better indicator of change for future assessments.

Equation 7.15

$$PF = (BS * 0.8) + (Con * 0.2)$$

where:
PF = *physical form theme score for the SWMA/zone (0–1)*
BS = *bank stability subindex score for the SWMA/zone (0–1) (from Equation 7.11)*
Con = *connectivity subindex score for the SWMA/zone (0–1) (from Equation 7.13).*

7.3 Results

7.3.1 Bank stability

Daly River

In 2009, 41 sites were surveyed in the Daly River catchment using the TRARC methodology (Dixon et al. 2006). This comprised 32 reaches in the developed zone and nine in the undeveloped zone. Sites were concentrated in first- and second-order streams in the developed zone. Only one or two sites per stream order were surveyed in the undeveloped zone. Nine sites met reference-site criteria and comprised two first-order streams, three second-order streams, one third-order, one fourth-order and two fifth-order streams.

TRARC erosion scores were converted to FARWH scores to produce: 1) an O/E score for each survey reach (Table 7.34; mean = 0.82 + sd 0.17, range = 0.42–1.00); 2) an average stream-order score; and 3) a final bank stability subindex score weighted for stream-order length (Equation 7.11). Final bank stability scores were 0.84 and 0.77 for the developed and undeveloped zones in the Daly River catchment (Table 7.35).

Table 7.34: Site results for the Bank Stability subindex in the Daly River SWMA, 2009.*

Site	Stream order	Zone	Bank stability subindex (0–1)	Site	Stream order	Zone	Bank stability subindex (0–1)
**DG01	2	D	1.00	**HY02	1	D	0.95
DG02	2	D	1.00	KA01	3	D	0.88
DP01	1	D	0.70	KA02	3	D	0.78
DY01	5	D	0.83	**KA03	3	D	1.00
**DY02	5	D	1.00	KA04	3	U	0.86
*DY03	5	U	0.91	KA05	2	U	1.00
DY04	5	U	1.00	KA06	3	U	0.49
ED01	1	U	1.00	KG01	4	U	0.42
**FL01	4	D	1.00	MD01	1	D	0.56
FL02	4	D	0.58	ME01	2	D	0.81
FP01	1	U	0.65	SC01	2	D	0.75
GA01	1	D	0.59	SM01	2	U	0.99
GA02	2	D	0.96	SN01	1	D	0.58
GA03	2	D	0.89	SN02	1	D	0.82
**GA04	2	D	0.88	SN03	1	D	0.71
GA05	3	D	0.96	SN04	1	D	0.79
GT01	1	D	0.79	SN05	2	D	1.00
GT02	1	D	0.88	ST01	2	D	0.86
GT03	1	D	0.66	ST02	2	D	0.76
GT04	1	D	0.95	ST03	1	D	0.55
**HY01	2	D	0.94				

*** Scores are converted from TRARC indicators of erosion (see Figure 7.18). Subindex scores are O/E ratios based on generic reference condition for each stream order. See Discussion below for limitations of this method. D = developed zone, U = undeveloped zone.**

** reference site

Table 7.35: Computation of the FARWH bank stability subindex for two Daly River strata: a) developed zone, and b) undeveloped zone. Final scores are the sum of stream-order length weighted scores. Scores are between 0–1.

(a) Developed zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Stream order length weighted score (W*A)
1st	243 (32%)	0.32	26	13 (50%)	0.73	0.23
2nd	184 (25%)	0.25	21	11 (52%)	0.90	0.22
3rd	127 (17%)	0.17	16	4 (25%)	0.90	0.15
4th	68 (9%)	0.09	6	2 (33%)	0.79	0.07
5th	125 (17%)	0.17	7	2 (29%)	0.91	0.16
Total	**747 km**		**76**	**32 (42%)**		**0.84**

(b) Undeveloped zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Stream order length weighted score (W*A)
1st	258 (31%)	0.31	17	2 (12%)	0.65	0.20
2nd	195 (23%)	0.23	17	2 (12%)	1.00	0.23
3rd	209 (25%)	0.25	24	2 (8%)	0.67	0.17
4th	52 (6%)	0.06	4	1 (25%)	0.42	0.03
5th	126 (15%)	0.15	11	2 (18%)	0.95	0.14
Total	**840 km**		**73**	**9 (12%)**		**0.77**

Fitzroy River

In 2009, 35 sites (3% of the 1191 FARWH reaches) were surveyed in the Fitzroy River catchment using the TRARC methodology (Ord River version, Dixon and Douglas 2007). Sites were geographically spread across the three Fitzroy subregions. Thirteen sites were located on small tributaries, 14 sites were sampled from the middle section of the Fitzroy River and eight from the upper regions of the catchment (Table 7.36; mean = 0.83 + sd 0.19, range = 0.36–1.00). Scores for each stream order were averaged and weighted for contributing length (Equation 7.11) to produce a final bank stability subindex score of **0.82** for the Fitzroy River SWMA (Table 7.37).

Table 7.36: Site results for the bank stability subindex in the Fitzroy River SWMA, 2009.#

Site	Stream Order	Sub-region	Bank stability Subindex (0–1)	Site	Stream order	Sub-region	Bank Stability Subindex (0–1)
1	2	M	0.90	16	1	S	1.00
2	2	M	0.85	24	1	S	1.00
4	1	M	0.81	28	2	S	0.56
5	5	M	0.40	* 30	1	S	1.00
6	5	M	0.71	31	3	S	1.00
7	5	M	1.00	32	3	S	1.00
*8	5	M	1.00	33	3	S	0.61
9	1	M	0.64	34	3	S	0.36
11	4	M	0.42	36	2	S	1.00
12	4	M	0.89	20	3	U	0.92
13	1	M	0.69	21	4	U	0.85
17	1	M	0.82	23	1	U	0.80
18	2	M	0.61	25	2	U	1.00
19	2	M	0.82	26	2	U	1.00
3	2	S	0.72	*27	2	U	1.00
10	3	S	1.00	29	1	U	0.89
14	1	S	1.00	35	1	U	0.91
15	1	S	0.92				

 # Scores are converted from TRARC indicators of erosion (see Figure 7.18). Subindex scores are O/E ratios based on generic reference condition for each stream order. See Discussion below for limitations of this method. Letters denote catchment subregions as: M, mid catchment,; S, small tributary, and; U, upper catchment.

*reference site

Table 7.37: Computation of the FARWH bank stability subindex for the Fitzroy River SWMA.*

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Stream order length weighted score (W*A)
1st	5904 (50%)	0.50	600	8 (1%)	0.88	0.43
2nd	2813 (24%)	0.24	261	2 (1%)	0.59	0.14
3rd	1872 (16%)	0.16	201	2 (1%)	1.00	0.16
4th	632 (5%)	0.05	71	7 (10%)	0.87	0.05
5th	225 (2%)	0.02	23	8 (35%)	0.90	0.02
6th	454 (4%)	0.04	35	8 (23%)	0.70	0.03
Total	**11900 km**		**1191**	**35 (3%)**		**0.82**

***Final scores are the sum of stream order length weighted scores. Scores are between 0–1.**

7.3.2 Connectivity

Daly River

Nine in-stream structures were identified in the Daly River catchment. Each structure was assigned a connectivity weighting (Table 7.38), with five structures receiving a zero weighting (i.e. negligible barrier to movement of aquatic biota). Reach connectivity scores were length-weighted to produce a final connectivity subindex score of **0.95** and **1.00** for the developed and undeveloped zones of the catchment, respectively.

Table 7.38: Instream structures in the Daly River catchment and connectivity weightings.

Structure name	Type	(a) Barrier weighting	(b) Seasonal weighting	Connectivity weighting (a*b)
Green Ant Ck weir	Weir (1 m wall)	1	0.5	0.5
Donkey Camp weir	Weir (2 m wall)	1	0.5	0.5
Katherine Low Level Crossing	Weir (1 m wall & spillway)	0.5	0.5	0.25
Knotts Crossing	Weir (0.8 m inclined spillway)	0.25	0.5	0.125
Daly River Crossing	Wet/dry causeway (5 chutes)	0.25	0	0
Beeboom Crossing	Wet/dry causeway (3 chutes)	0.25	0	0
Oolloo Crossing	Rock ford (submersed)	0.25	0	0
Claravale Crossing	Wet causeway (submersed)	0.25	0	0
Douglas River weir	Weir (0.3 m wall)	0	0.5	0

Fitzroy River

The Camballin Barrage is the only major artificial barrier to fish migrations on the main channel of the Fitzroy River. A smaller weir (Myroodah Crossing) also exists downstream of the barrage. In most years (~80%) since 1987 the barrage was only negotiable by fish for up to three months/year, even though flows may continue for much of the year (Morgan et al. 2005). Connectivity scores were not calculated for each reach. However, after evaluating the Daly River scores above, we assigned a nominal score of 0.99 for the Fitzroy River SWMA.

7.3.3 Integration to the physical form theme

Daly River

Using Equation 7.15, bank stability and connectivity subindex scores were integrated to produce a final physical form theme score of **0.86** and **0.82** for the developed and undeveloped zones in the Daly River catchment (Table 7.39). Subindex scores for the Daly River SWMA were calculated using Equation 4.8 to produce a final physical form theme score of **0.84**.

Table 7.39: Integration of the bank stability and connectivity subindices to produce a physical form theme score for the developed and undeveloped zones of the Daly River catchment. Scores are between 0–1.

SWMA	Bank stability Subindex (80%)	Connectivity subindex (20%)	Physical form theme
Developed zone	0.84	0.95	**0.86**
Undeveloped zone	0.77	1.00	**0.82**
Daly River SWMA	**0.80**	**0.98**	**0.84**

Fitzroy River

Using Equation 7.15, bank stability and connectivity subindex scores were integrated to produce a final physical form theme score of **0.85** for the Fitzroy River SWMA (Table 7.40).

Table 7.40: Integration of the bank stability and connectivity subindices to produce a physical form theme score for Fitzroy River SWMA. Scores are between 0–1.

SWMA	Bank stability subindex (80%)	Connectivity subindex (20%)	Physical form theme
Fitzroy River	0.82	0.99	**0.85**

7.4 Discussion

Bank stability

Discussion topics for the Bank Stability subindex are similar to those presented in Chapter 8, ‘Fringing zone theme’.

This field trial used on-ground assessment of erosion features at a limited number of sites within each SWMA. Only a small proportion of reaches were accessible, given the available resources and permission, and the enormity and remoteness of the catchments. In the Fitzroy River catchment, 90% of the subindex score was derived from only 1% of the first-, second- and third-order reaches (Table 7.37). Furthermore, the actual length of stream assessed (200 m of reach at 35 sites = 7 km) represented only 0.06% of 11900 km of stream network in the SWMA. Consequently, integration of site scores to the SWMA presented here need to be interpreted with caution.

Reference condition (‘expected’ condition) was defined as sites with minimal disturbance. Because of our limited knowledge of the natural variability of bank stability and the range of natural geomorphic types, caution is required when interpreting these FARWH results. Sites were compared to an expected condition defined for stream order (Daly River) or bioregion (Fitzroy River). Australian tropical rivers are highly variable and may require separation into more complex classifications; therefore we acknowledge that more intensive research is required to properly define reference condition. For example, the difference in scores between the developed and undeveloped zones in the Daly River catchment (0.84 and 0.77, respectively) could be explained by natural variability of stream geomorphology at the study sites. For example, sites in the developed zone were often narrow deep channels with closed-forest riparian vegetation and black/clay soils (Figure 7.19), whereas many sites in the undeveloped zone had wide, shallow, braided channels, with sandy soils and sparser riparian vegetation, and therefore had less-stable banks and more exposed soil (Figure 7.19). The natural difference between these zones is not considered as sites with the same stream order are compared to the same expected reference condition.

Figure 7.19:Two third-order streams in the Daly River SWMA that have contrasting bank characteristics, but are compared to the same generic reference condition when computing O/E scores. Green Ant Creek (GA05, left) has a single channel with clay soils, rocky substrate, exposed bedrock and dense closed-forest riparian vegetation. Katherine River (KA06, right) has braided channels with sandy soils and a more open paperbark riparian community.

As a comparison, the bank stability scores for the Fitzroy River SWMA and Daly developed zone are lower than scores recorded in the Darwin Harbour and Ord River SWMAs (**Table 7.41**; Dixon et al. 2009). However, the method used to integrate the TRARC erosion scores to the bank stability subindex was different to that used in this study (see Chapter 7.1.1, ‘Data analysis’, and Appendix 13.6)*;* thus, the results are likely to overscore the bank stability subindex. For fair cross-SWMA comparison of these FARWH scores, the results of the desktop study (Dixon et al. 2009) would need to be recalculated using the integration method presented in this study.

Table 7.41: Bank stability results from this study and the desktop trial of FARWH in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009).*

Stream Order	Daly River: Developed	Daly River: Undeveloped	Fitzroy River	Darwin Harbour	Ord River
1st	0.73	0.65	0.88	0.97*	0.92*
2nd	0.90	1.00	0.59	0.93*	0.83*
3rd	0.90	0.67	1.00	0.94*	0.89*
4th	0.79	0.42	0.87	0.95*	0.84*
5th	0.91	0.95	0.90	-	-
6th	-	-	0.70	-	-
Final score	**0.84**	**0.77**	**0.82**	**0.96***	**0.88***

*** Scores are weighted to stream-order length to produce a final score (0–1). *Note: scores for Darwin Harbour and Ord River are integrated using a different method, thus likely overscore the bank stability subindex (see Chapter 7.1.1, 'Data analysis').**

The current GIS dataset of geomorphic classes was not suitable for this study because of the low resolution and large scale. Geomorphic classification tools are currently being developed that will address the scale and diversity of natural fluvial geomorphology in tropical rivers (e.g. Spencer et al. 2007). We recommend that future development of FARWH in the wet/dry tropics use this tool, or similar, when available. Also, as remotely sensed data becomes more widely available and more accurate, the potential to apply remote, catchment-scale erosion assessments should also be considered in future FARWH assessments (e.g. Brooks et al. 2008).

Future development of the FARWH bank stability subindex should consider the following:

1) Critical knowledge of expected condition is lacking for the various types of geomorphic stream types in the study catchments. Utilising new tools that identify reaches for their unique character would help identify expected bank stability condition for any site.

2) Investigation of the natural variability of erosion features is required. This may include variables such as soil type, bank slope and height, stream power, riparian vegetation cover and position in the catchment. While geomorphic river classifications (above) may include such features, identification of other smaller-scale features will likely require on-ground assessments.

3) A movement from on-ground surveys to remotely sensed data (e.g. satellite imagery) would be ideal given the large catchment area and remoteness of many tropical rivers. Investigation into the type of bank characteristics and their ecological importance would be required to inform assessment protocols. Currently, both processing time and experienced staff are important limitations on adopting these techniques. Results from this study could assist in ground-truthing future development of remote sensing.

Connectivity

When compared to southern catchments, there are relatively few in-stream structures that pose a barrier to movement of aquatic biota. Therefore, we cannot fully comprehend the impact of large-scale development. Limitations to the methods presented in this study are:

- Weightings for the impact of barrier types to movement of fish are subjective.
- It is unclear how these barriers may obstruct movement of other aquatic biota such as

turtles and macroinvertebrates. Crocodile access is not considered relevant as they are known to travel large distances overland to search for water (~1km) and could navigate barriers via riparian zones.

- A generalised approach has been adopted from NWC (2007). Only limited information was used on the upstream/downstream migration of spawning fish (e.g. barramundi), and the search for dry season refugia.

These issues may need to be evaluated as development pressures increase across northern Australia.

Comparison with the desktop trials in the Darwin and Ord SWMAs is not recommended, as the methods used in Dixon et al. (2009) did not cap the impact of barriers at 40 km up/downstream (Table 7.42). The low score for the Ord River can be explained by the methodology employed and the presence of two large barriers located in the lower catchment. In contrast, the Darwin River is one of many drainage systems in the Darwin Harbour catchment, thus the impact is connected to the majority of the SWMA. For true comparison between SWMAs, it is recommended that methods used in the desktop trials be modified to match those presented in this study.

Table 7.42: Connectivity results from this study and the desktop trial of FARWH in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009).#

	Daly River: developed	Daly River: undeveloped	Fitzroy River	Darwin Harbour	Ord River
Final score	0.95	1.00	0.99	0.91*	0.14*

 # In the Daly and Fitzroy river SWMAs, barrier weightings are applied for reaches within 40 km upstream and downstream of a barrier; however, in the *Darwin Harbour and *Ord River SWMAs, weightings are not capped at 40 km. As a consequent, the Ord River scores substantially lower.

Integration to a physical form subindex

Bank stability was given a higher weighting (80%) than connectivity (20%), as erosion is more likely to vary in the future than the number of large dams or weirs in the catchment. Thus, it provides a better indicator of change for future assessments. A level of complexity is added to the integration process because bank stability is an on-ground assessment at a limited number of sites; whereas connectivity is a desktop assessment that can be applied to the entire SWMA. If the two subindices were integrated to the theme level at a reach scale, and then aggregated to an SWMA scale, valuable information on connectivity would be lost (i.e. reaches without on-ground assessment would be ignored). Alternatively, by using the methods presented in this study, independent aggregation of subindices to the SWMA level before integration to a theme score allows for the inclusion of all available data—and meets land management interest—but does not allow for a reach-level theme score. Because of the differences between methods in this study and the desktop trials in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009), the reader should not interpret that one catchment is better or worse than another until all methods of assessment and integration are refined to match those presented in this study (Table 7.43).

Table 7.43: Physical form theme results from this study and the desktop trial of FARWH in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009).#

Subindex	Daly River: developed	Daly River: undeveloped	Fitzroy River	Darwin Harbour	Ord River
Bank stability (80%)	0.84	0.77	0.82	0.96*	0.88*
Connectivity (20%)	0.95	1.00	0.99	0.91*	0.14*
Final score	**0.84**	**0.77**	**0.82**	**0.95***	**0.73***

 # Subindices are weighted 80% for bank stability and 20% for connectivity. produce a final score (0-1). *Note: scores for Darwin Harbour and Ord River are integrated using a different method to this study (see Discussion above).

In conclusion, this study attempted to compare field measurements of bank condition to a stream order-based reference condition in the Daly River. This comparative technique is inadequate because of the natural differences of geomorphic type within the study catchments and lack of representative reference sites. In contrast, the Fitzroy River trial used reference conditions at a bioregional scale. Although the results from the Fitzroy River appear to be more representative of site conditions, further investigation of the natural variability and corresponding reference condition is required to further develop the bank stability subindex. In addition, the sheer size of the catchments reduces the efficiency of on-ground assessment approaches and results in the calculation of SWMA scores based on assessment of a very small proportion of the entire stream network. Scores presented here should therefore be interpreted with caution until suitable reference conditions are determined. The connectivity assessment appears suitable given the current development levels in northern Australia.

7.5 Literature cited

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8 Fringing zone theme

8.1 Introduction

The fringing zone theme is an assessment of riparian vegetation condition. Riparian zones can be broadly defined as the land that adjoins, or directly influences, a body of water (Price and Lovett 2002), including the riverbank and floodplain. For the purpose of the fringing zone theme in the wet/dry tropics, we define the riparian zone as the area extending from the edge of the river channel to where there is a distinct change in vegetation and landform. Across northern Australia, this riparian zone is usually a distinct green belt dissecting a sparsely vegetated savanna landscape. Because of the limited clearing of riparian vegetation in the wet/dry tropics, assessment using remote sensing would only provide information on vegetation width and longitudinal continuity—features we know are relatively undisturbed. With management activities focused on localised disturbances caused by weeds, overgrazing, fire and feral animals (pressures more likely to affect the understorey), on-ground assessment is more appropriate when applied at manageable scales. This chapter aims to calculate the fringing zone theme based on on-ground assessments and identify challenges in its application.

8.2 Methods

We applied an existing on-ground riparian assessment methodology—TRARC—in the Daly and Fitzroy river catchments. TRARC requires visual assessment of riparian condition indicators, including plant cover and regeneration; and the occurrence of weeds, erosion and other pressures (Dixon et al. 2006). TRARC uses a standard 100 m transect running parallel to the stream. In these trials, up to four transects were placed over a distance of 250 m (two on each bank 50 m apart). The exception was on larger rivers, when crossing to the opposite bank was not possible. In such cases two transects were placed on one bank only. TRARC field procedures followed those described in Dixon et al. (2006).

Reference condition

No model currently exists to predict the reference condition of riparian zones in the Australian wet/dry tropics. Thus, reference, or expected, condition for the fringing zone theme was determined from sites with minimal disturbance in the region. Reference sites from both within focal catchments and from adjacent catchments were nominated for each stream order (Daly River catchment) or region (Fitzroy River catchment). Sites needed to meet five criteria to be considered for reference condition:

1) Have ‘good–excellent’ TRARC condition scores (i.e. 80–100)

2) Have ‘low’ TRARC pressure scores (i.e. 0–24)

3) Have less than 10% clearing within a 1km radius of the site

4) Have no large dams upstream

5) Not be a unique site (e.g. plunge pool below a waterfall).

Criteria 1 and 2 were developed from desktop trials in the Darwin Harbour and Ord River catchments, which showed that sites with low pressure were generally in better condition (Dixon et al. 2009). Criterion 3 originates from testing the TRARC data in the Darwin Harbour catchment (Dixon 2006), which showed 14 TRARC indicators and indices were correlated to clearing of native vegetation within a 1 km radius of the site ($r = 0.35\text{-}0.75$; $p < 0.05$). Unlike in-stream health, which is mostly influenced by upstream parameters, riparian zones can be affected by local, site-specific pressures such as overgrazing, feral animals, fire and weeds (Bartolo et al. 2008). The percentage of cleared vegetation is used here as a surrogate for these pressures. Criterion 4 recognises that regulated flow can alter structure and recruitment potential of downstream riparian communities (Doupe and Pettit 2002; Start 2000). Criterion 5 removes sites that are not representative of the greater proportion of stream characteristics. For example, riparian zones surrounding plunge pools below waterfalls are often very different, owing to microsite characteristics, including water permanence and local geomorphology.

Using these five criteria, nine sites were identified as reference sites for the Daly River catchment. In the Fitzroy River catchment, three reference sites were selected, based on similar criteria for each subregion (see Chapter 3.4.2). Non-reference sites were compared to reference sites by using the calculations described below.

Data analysis

Before converting scores from TRARC to FARWH, one important modification was made to the TRARC grass-cover scores. In its original form, it was not possible for TRARC to achieve a maximum canopy-cover and grass-cover score (simultaneously) because of greater tree cover naturally shading out grasses. To compensate for this, ‘expert rules’ were used to recalculate grass-cover scores, based on their matching canopy-cover scores (Equation 8.16). For example, if canopy cover exceeded 75%, then grass cover was given the highest possible score even though there may have been little grass present. All sites were modified using the same rules, allowing sites to be compared on an observed versus expected (O/E) basis.

Equation 8.16

If $C \geq 4.5$, then $d = 5.0$
If $C \geq 3.5$ and $G \geq 2.5$, then $d = 5.0$
If $C \geq 3.5$ and $G \geq 1.5$ and < 2.5, then $d = 3.0$
If $C \geq 3.5$ and $G < 1.5$, then $d = 1.0$
If $C \geq 2.5$ and $G \geq 3.5$, then $d = 5.0$
If $C \geq 2.5$ and $G \geq 1.5$ and < 3.5, then $d = 3.0$
If $C \geq 2.5$ and $G < 1.5$, then $d = 1.0$
If $C < 2.5$, then $d = G$

where:
C = *original TRARC canopy cover score*
G = *original TRARC grass cover score*
d = *converted grass cover score.*

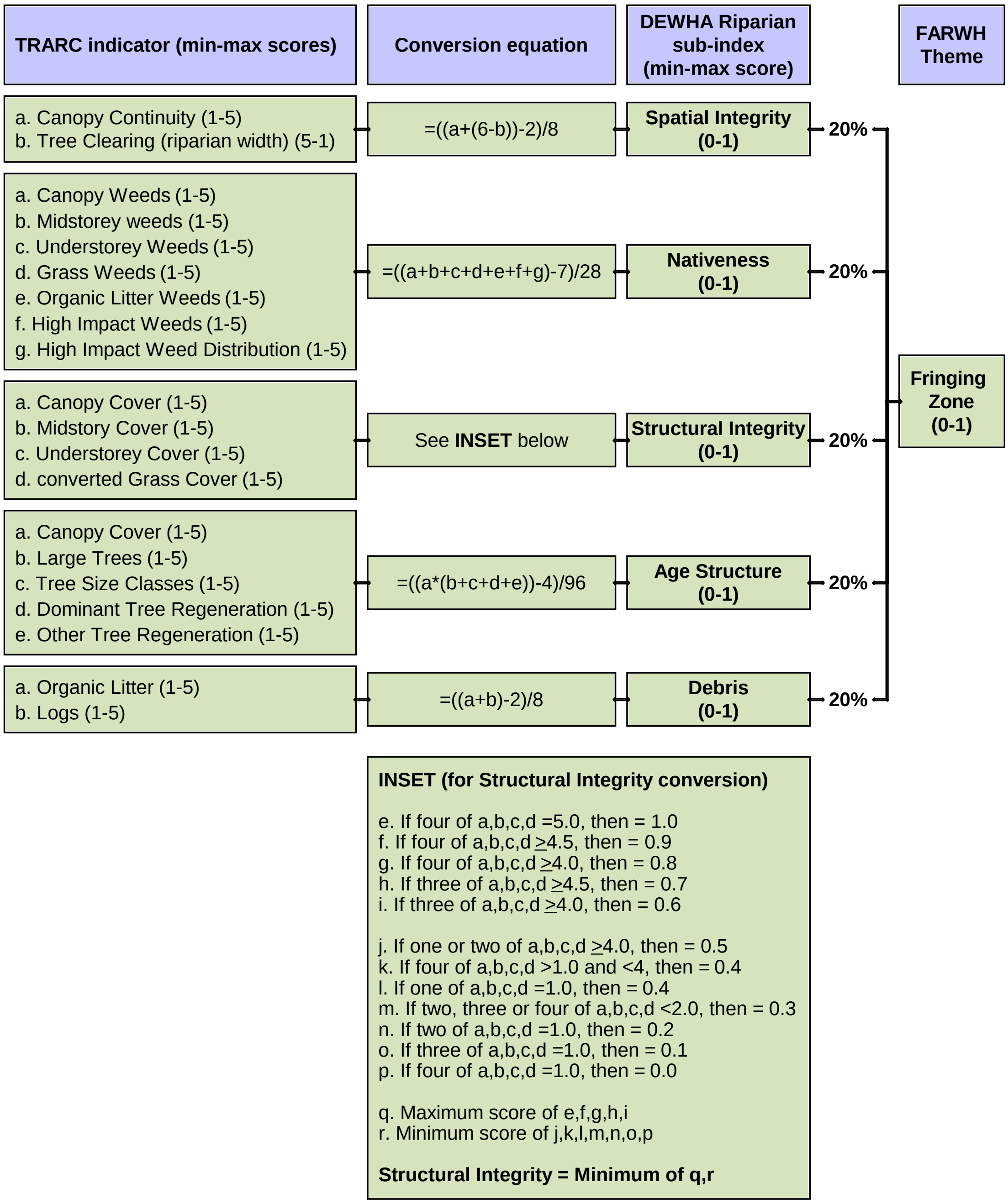
After correcting grass-cover scores, TRARC indicators were recalculated into five nationally comparable subindices as defined in the *National interim protocol for assessing riverine (riparian) vegetation* (DEWHA 2008): spatial integrity, nativeness, structural integrity, age structure and debris (Table 8.44).

Table 8.44: Recommended *National interim protocol for assessing riverine (riparian) vegetation condition* (from DEWHA 2008).

	Largely unmodified (1–0.8)	**Slightly modified (0.8–0.6)**	**Moderately modified (0.6–0.4)**	**Substantially modified (0.4–0.2)**	**Severely modified (0.2–0)**
SPATIAL INTEGRITY	No or little evidence of broadscale loss of native vegetation.	Width reduced by up to 1/3 and/or some breaks in continuity.	About 50% of the native vegetation remains, either in strips or patches.	Only small patches of well-separated native vegetation remain.	Little or no remaining native vegetation.
NATIVENESS	Vegetation predominantly native, few weeds and no 'high threat' species.	Exotic species present but not dominating any strata, 'high threat' species rare.	One or more strata dominated by exotic species, 'high threat' species present.	Most strata dominated by exotic species, 'high threat' species abundant.	Few native species remaining, cover dominated by exotic species.
STRUCTURAL INTEGRITY	Number of strata and cover within each similar to reference.	Cover within one stratum up to 50% lower or higher than reference.	One stratum missing or extra, cover within remaining strata 50% lower or higher than reference	More than one stratum completely altered from reference (lost or <10% remaining).	Structure completely altered from reference (e.g. grassland shrubland, forest pasture).
AGE STRUCTURE	Dominant strata with reference level of cover and at least three age classes present (juveniles, sub-adults and adults).	Reduced cover (75–50%) of dominant strata, and/or only two age classes present.	Reduced cover (75–50%) of dominant strata, and only one age class present.	Reduced cover (<50%) of dominant strata, and only one age class present.	Dominant strata mostly absent.
DEBRIS	Quantities and cover similar to reference.	Some evidence of unnatural loss of debris (e.g. through collection of firewood, trampling of leaf litter by stock).	Quantities and/or cover 50% higher or lower than reference.	Very small quantities of debris present.	Debris mostly absent or completely dominating the sites, with little or no living vegetation.

Calculations were mostly averages of TRARC indicators, but also included 'expert rules' (structural integrity) and multiple weighting (canopy cover in age structure) (Figure 8.20). The interim DEWHA riparian protocol recommends the use of remotely-sensed data for determining spatial integrity (i.e. riparian width and continuity). Because this resource was not used in this study we applied the canopy continuity and tree-clearing indicators of TRARC. Riparian width is not scored using TRARC. Instead, the tree-clearing indicator of TRARC (see Dixon et al. 2006), which measures the extent of riparian/buffer clearing, was inverted and applied as a surrogate measure of riparian width.

Figure 8.20: Conversion process of TRARC scores to DEWHA riparian subindices and final FARWH fringing zone score.



Using the criteria discussed above, reference sites were selected to represent each stream order (for the Daly River catchment) and subregion (for the Fitzroy River catchment). With the exception of the nativeness subindex, reference site scores were averaged to produce an 'expected' subindex score (Table 8.44). In the case of nativeness, reference condition was defined as no weeds. For each stream order or subregion, scores for test sites (i.e. 'observed' (O) scores) where compared to the 'expected' (E) reference scores, resulting in an O/E score for each subindex. Because of limited understanding of the natural variability of riparian zones and reference condition, a decision was made to cap O/E scores that exceeded 1.0—i.e. test sites with greater vegetation cover or abundance than reference sites (O/E >1.0) were capped at 1.0 and not scaled lower to reflect any difference from ‘expected’. A fringing zone theme score was then taken as the average of five O/E subindex scores at each site (Figure 8.20).

Aggregation of scores

Although not required for this study (reaches were represented by only one site), sites within the same reach should be averaged to give a FARWH reach score. Reach O/E scores were averaged for each stream order and weighted for contributing length of total stream network to produce a final fringing zone theme score (Equation 8.17).

Equation 8.17

$$FZ = ((L_{S1} / L_{SN} * S_{A1}) + (L_{S2} / L_{SN} * S_{A2}) + (L_{S3} / L_{SN} * S_{A3}) + \ldots)$$

where:
FZ = *final fringing zone FARWH score (0–1)*
L_{S1} = *combined length of all 1^st^ order streams (L_{S2} = 2^nd^ order etc.)*
L_{SN} = *total length of entire stream network*
S_{A1} = *average riparian score for 1^st^ order streams (S_{A2} = 2^nd^ order etc.).*

For the Daly River SWMA, where scores have been aggregated to a stratified zone (developed and undeveloped), an additional step is required to calculate a final fringing zone theme score. Stratified zone scores were weighted by contributing stream length to the total SWMA perennial network: developed zone = 747 km (47%) of perennial streams; undeveloped zone = 840 km (53%) of perennial streams (Equation 4.8).

Equation 8.18

$$FZ = (FZ_D * 0.47) + (FZ_U * 0.53)$$

where:
FZ = *fringing zone theme score for Daly River SWMA (0–1)*
FZ_D = *fringing zone theme score for Daly River developed zone (0–1)*
FZ_U = *fringing zone theme score for Daly River undeveloped zone (0–1).*

8.3 **Results**

Daly River

In 2009, 41 sites were surveyed in the Daly River catchment using the TRARC methodology (Dixon et al. 2006). Nine sites (Table 8.45) met reference site criteria and comprised two first-order, three second-order, one third-order, one fourth-order and two fifth-order streams. One reference site was located in the adjacent catchment. TRARC scores were converted to FARWH scores, to produce: 1) an O/E score for each survey reach (Table 8.45; mean = 0.81 ± sd 0.12; range = 0.48 - 1.00); 2) an average stream order score; and 3) a final FARWH fringing zone score weighted for stream-order length (using Equation 8.17). Final scores for the developed and undeveloped zones of the Daly River catchment were 0.83 and 0.77 respectively (Table 8.46). Aggregation of these scores to the SWMA (using Equation 4.8) produced a final fringing zone theme score of **0.80** (Table).

Table 8.45 Site results for the fringing zone theme in the Daly River SWMA, 2009.*

Site	Stream order	Zone	Spatial integrity	Native-ness	Structural integrity	Age structure	Debris	Fringing zone theme (0–1)
*DG01	2	D	1.00	1.00	1.00	1.00	1.00	1.00
DG02	2	D	1.00	1.00	0.60	0.59	0.90	0.82
DP01	1	D	1.00	0.99	0.73	0.77	0.81	0.86
DY01	5	D	1.00	0.85	1.00	0.92	1.00	0.95
*DY02	5	D	1.00	1.00	1.00	0.96	0.89	0.97
*DY03	5	U	1.00	0.85	0.86	1.00	1.00	0.94
DY04	5	U	1.00	0.87	1.00	0.64	0.81	0.86
ED01	1	U	0.77	0.93	1.00	0.80	0.67	0.83
*FL01	4	D	1.00	1.00	1.00	1.00	1.00	1.00
FL02	4	D	0.63	0.77	1.00	0.40	1.00	0.76
FP01	1	U	0.65	0.80	0.55	0.39	0.49	0.57
GA01	1	D	0.65	0.74	0.73	0.89	1.00	0.80
GA02	2	D	0.67	0.64	0.80	0.52	0.84	0.69
GA03	2	D	0.63	0.89	0.60	0.81	0.67	0.72
*GA04	2	D	1.00	0.76	1.00	0.96	0.95	0.93
GA05	3	D	0.72	0.83	1.00	0.80	0.97	0.86
GT01	1	D	0.71	0.73	0.73	0.52	0.43	0.62
GT02	1	D	0.84	0.92	0.55	0.79	1.00	0.82
GT03	1	D	0.77	0.51	0.91	0.89	1.00	0.82
GT04	1	D	0.58	0.58	0.91	1.00	1.00	0.81
*HY01	2	D	1.00	1.00	1.00	1.00	1.00	1.00
*HY02	1	D	0.97	1.00	0.91	0.86	0.84	0.91
KA01	3	D	0.75	0.91	1.00	0.83	0.78	0.85
KA02	3	D	0.75	0.93	1.00	0.62	0.57	0.77
*KA03	3	D	1.00	0.96	1.00	1.00	1.00	0.99
KA04	3	U	1.00	1.00	1.00	0.66	0.65	0.86
KA05	2	U	1.00	1.00	0.60	0.14	0.34	0.62
KA06	3	U	1.00	1.00	1.00	0.74	0.86	0.92
KG01	4	U	0.88	1.00	1.00	0.98	0.94	0.96
MD01	1	D	0.97	0.95	0.55	0.85	0.92	0.85
ME01	2	D	1.00	0.93	0.80	0.64	0.64	0.80
SC01	2	D	1.00	0.93	0.80	0.71	0.51	0.79
SM01	2	U	1.00	0.86	0.80	0.82	0.80	0.86
SN01	1	D	0.06	0.59	0.55	0.29	0.93	0.48
SN02	1	D	0.45	0.63	0.73	0.54	1.00	0.67
SN03	1	D	0.39	0.80	0.55	0.48	0.84	0.61
SN04	1	D	0.65	0.79	0.73	0.77	0.86	0.76
SN05	2	D	0.60	0.81	0.80	0.56	0.78	0.71
ST01	2	D	1.00	0.96	0.60	0.68	0.54	0.76
ST02	2	D	1.00	1.00	0.80	0.60	0.46	0.77
ST03	1	D	0.71	0.89	0.73	0.65	0.76	0.75

 # Scores are converted from the TRARC indicators and grouped into five DEWHA riparian subindices (see Figure 8.20). Subindex scores are O/E ratios based on generic reference condition for each stream order. See Discussion below for limitations of this method.
D = developed zone; U = undeveloped zone.

*reference sites

Table 8.46: Stream order scores and final calculation of the FARWH fringing zone theme for the two stratified zones in the Daly River catchment: a) developed, and b) undeveloped.

a) Developed zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Weighted score (W*A)
1st	243 (32%)	0.32	26	13 (50%)	0.75	0.24
2nd	184 (25%)	0.25	21	11 (52%)	0.82	0.20
3rd	127 (17%)	0.17	16	4 (25%)	0.87	0.15
4th	68 (9%)	0.09	6	2 (33%)	0.88	0.08
5th	125 (17%)	0.17	7	2 (29%)	0.96	0.16
Total	**747 km**		**76**	**32 (42%)**		**0.83**

b) Undeveloped zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Weighted score (W*A)
1st	258 (31%)	0.31	17	2 (12%)	0.57	0.18
2nd	195 (23%)	0.23	17	2 (12%)	0.77	0.18
3rd	209 (25%)	0.25	24	2 (8%)	0.89	0.22
4th	52 (6%)	0.06	4	1 (25%)	0.96	0.06
5th	126 (15%)	0.15	11	2 (18%)	0.90	0.14
Total	**840 km**		**73**	**9 (12%)**		**0.77**

*** Final scores use stream order length-weighted scores (from Equation 8.17). Scores are between 0–1.**

Table 8.47: Aggregation of fringing Zone theme scores for the Daly River SWMA.*

SWMA	Zone score (z)	Weighting (w)	(w * z)
Developed zone	0.83	0.47	0.39
Undeveloped zone	0.77	0.53	0.41
Daly River SWMA			**0.80**

*** The developed and undeveloped zone scores are weighted for contributing length of perennial streams to the total SWMA perennial network (Equation 4.8). Scores are between 0–1.**

Fitzroy River

In 2009, 35 sites (3% of the 1191 FARWH reaches) were surveyed in the Fitzroy River catchment using the TRARC methodology (Dixon and Douglas 2007). TRARC scores were converted to FARWH scores, to produce: 1) an O/E score for each survey reach (Table 8.48; mean = 0.77 ± sd 0.15; range = 0.43 - 0.98); 2) an average stream-order score; and 3) a final FARWH fringing zone score weighted for stream order length (Equation 8.17). A final fringing zone theme score of **0.86** was calculated for the Fitzroy SWMA (Table 8.49).

Table 8.48: Site results for the fringing zone theme in the Fitzroy River SWMA, 2009.#.

Site	Stream order	Sub-region	Spatial integrity	Native-ness	Struct-ural integrity	Age struct-ure	Debris	Fring-ing zone theme (0-1)
FARWH_1	2	M	1.00	0.77	0.80	0.72	0.88	**0.83**
FARWH_2	2	M	1.00	0.64	0.80	0.59	0.96	**0.80**
FARWH_4	1	M	1.00	0.60	1.00	0.69	0.55	**0.77**
FARWH_5	5	M	0.52	0.54	0.80	0.25	0.46	**0.51**
FARWH_6	5	M	1.00	0.82	0.80	0.64	0.51	**0.75**
FARWH_7	5	M	1.00	0.38	1.00	0.46	0.77	**0.72**
*FARWH_8	5	M	1.00	0.88	1.00	1.00	1.00	**0.98**
FARWH_9	1	M	0.75	0.57	0.80	0.15	0.36	**0.53**
FARWH_11	4	M	0.75	0.79	0.60	0.14	0.20	**0.50**
FARWH_12	4	M	1.00	0.59	1.00	0.74	0.55	**0.78**
FARWH_13	1	M	1.00	0.57	1.00	0.72	0.68	**0.80**
FARWH_17	1	M	1.00	0.43	1.00	0.72	0.57	**0.74**
FARWH_18	2	M	1.00	0.58	0.80	0.57	1.00	**0.79**
FARWH_19	2	M	1.00	0.66	1.00	0.78	0.53	**0.79**
FARWH_3	2	S	1.00	0.51	0.80	0.44	1.30	**0.81**
FARWH_10	3	S	1.00	0.81	0.80	0.40	1.00	**0.80**
FARWH_14	1	S	1.00	0.91	0.60	0.36	1.00	**0.77**
FARWH_15	1	S	0.26	0.45	0.60	0.14	0.70	**0.43**
FARWH_16	1	S	1.00	0.57	0.80	0.45	1.00	**0.76**
FARWH_24	1	S	1.00	0.69	1.00	1.00	1.00	**0.94**
FARWH_28	2	S	1.00	0.92	1.00	1.00	0.97	**0.98**
*FARWH_30	1	S	1.00	0.81	1.00	1.00	1.00	**0.96**
FARWH_31	3	S	1.00	0.90	0.80	1.00	1.00	**0.94**
FARWH_32	3	S	1.00	0.84	1.00	0.63	0.97	**0.89**
FARWH_33	3	S	1.00	0.85	1.00	0.98	1.00	**0.97**
FARWH_34	3	S	1.00	0.99	1.00	0.63	0.97	**0.92**
FARWH_36	2	S	0.84	0.77	0.60	0.26	0.70	**0.63**
FARWH_20	3	U	0.87	0.77	1.00	0.25	0.60	**0.70**
FARWH_21	4	U	1.00	0.81	1.00	0.47	0.48	**0.75**
FARWH_23	1	U	0.96	0.59	1.00	0.61	0.71	**0.77**
FARWH_25	2	U	0.70	0.95	0.75	0.21	0.14	**0.55**
FARWH_26	2	U	0.70	0.96	1.00	0.22	0.36	**0.65**
*FARWH_27	2	U	1.00	0.90	1.00	1.00	1.00	**0.98**
FARWH_29	1	U	0.87	0.80	0.75	1.00	0.79	**0.84**
FARWH_35	1	U	0.61	0.48	1.00	0.58	0.57	**0.65**

 # Scores are converted from the TRARC indicators and grouped into five DEWHA 'riparian' subindices (see Figure 8.20). Subindex scores are O/E ratios based on generic reference condition for each region. See Discussion below for limitations of this method. Letters denote catchment regions as: M, mid-catchment; S, small tributaries and U, upper-catchment.
*reference site

Table 8.49: Stream-order scores, combined length and final calculation of the FARWH fringing zone theme for the Fitzroy River SWMA.*

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Weighted Score (W*A)
1st	5904 (50%)	0.50	600	8 (1%)	0.74	0.36
2nd	2813 (24%)	0.24	261	2 (1%)	0.64	0.15
3rd	1872 (16%)	0.16	201	2 (1%)	0.77	0.12
4th	632 (5%)	0.05	71	7 (10%)	0.74	0.04
5th	225 (2%)	0.02	23	8 (35%)	0.90	0.02
6th	454 (4%)	0.04	35	8 (23%)	0.74	0.03
Total	**11900 km**		**1191**	**35 (3%)**		**0.72**

*** Final scores use stream-order length-weighted scores (from Equation 8.17). Scores are between 0–1.**

8.4 Discussion

Discussion topics for the fringing zone theme are similar to those presented in Chapter 7, 'Physical form (bank stability)'.

This field trial used on-ground assessments of riparian vegetation features at a limited number of sites within each SWMA. Only a small proportion of reaches were accessible given the available resources and permission, and the enormity and remoteness of the catchments. In the Fitzroy River catchment, 90% of the subindex score was derived from only 1% of the first-, second- and third-order reaches (Table 8.49). Furthermore, the actual length of stream assessed (200 m of reach at 35 sites = 7 km) only represented 0.06% of the 11 900-km stream network within the SWMA. While this was unavoidable within the constraints that these trials were undertaken, the small proportion of the total stream network assessed creates uncertainty around the interpretation of the results.

Reference condition was defined as sites with minimal disturbance. Because of our limited knowledge of the natural variability of riparian community structure and the range of natural geomorphic types (which influence community structure), caution is required when interpreting these FARWH results. Sites were compared to an expected condition defined for each stream order (Daly River) or subregion (Fitzroy River). Australian tropical riparian zones are highly variable and may require separation into more complex classifications; therefore we acknowledge that more intensive research is required to properly define reference condition. For example, the difference in scores between the developed and undeveloped zones in the Daly River catchment (0.83 and 0.77 respectively) could be explained by natural characteristics such as soil type, stream flow, sediment regimes, bedrock characteristics, species composition and morphology (Dowe 2008). Sites in the developed zone were mostly narrow deep channels with closed-forest riparian vegetation and black/clay soils, whereas many sites in the undeveloped zone were often wide, shallow, braided channels, with gentle banks, sandy soils and sparser paperbark vegetation. The natural difference between these zones is not considered because sites with the same stream order are compared to the same expected reference condition. As a comparison, the fringing zone scores in the Fitzroy River SWMA and Daly developed zone are similar to scores recorded in the Darwin Harbour and Ord River SWMAs (Table 7.41; Dixon et al. 2009). However, the lowest-scoring region is the Daly River undeveloped zone (0.77). This indicates that the lack of reference sites in this study is a limitation to the suitability of FARWH as a cross-SWMA comparative tool. Until more appropriate reference sites are identified, caution should be applied when interpreting the results presented in this study.

Table 8.50: Fringing zone results from this study and the desktop trial of FARWH in the Darwin Harbour and Ord River SWMAs (Dixon et al. 2009).*

Stream order	Daly River: developed	Daly River: undeveloped	Fitzroy River	Darwin Harbour	Ord River
1st	0.75	0.57	0.79	0.83	0.88
2nd	0.82	0.77	1.00	0.84	0.90
3rd	0.87	0.89	0.95	0.94	0.87
4th	0.88	0.96	0.78	0.95	0.75
5th	0.96	0.90	0.79	-	-
6th	-	-	0.71	-	-
Final score	**0.83**	**0.77**	**0.86**	**0.84**	**0.87**

*** Scores are weighted to stream-order length to produce a final score (0–1).**

We recommend that future development of the fringing zone theme include investigation into the natural variability of riparian vegetation communities; including soil type, geomorphic class and species composition. As a guide, three examples of determining reference scores are presented in Table 8.51.

Differences between these sites are based on contrasting geomorphic types from field observations. Here, we have selected reference sites (relatively undisturbed) and scaled their subindex scores up to 1.0. The exception to this is the nativeness subindex, which remains unaltered, as reference condition is defined as 'no weeds' (i.e. a score of 1.0). Future development of this procedure would require reaches to be identified by their geomorphic class and allocated a comparative reference site with matching features and stream order. Raw subindex scores could then be scaled using a matching multiplier and capped at 1.0. In addition, the TRARC protocol could be reviewed to identify redundant indicators. It may be apparent that the number of assessment items could be reduced to save field time and/or be tailored to remote sensing, while achieving a similar result.

In conclusion, this study attempted to compare field measurements of riparian condition to a stream order-based reference condition in the Daly River catchment. This comparative technique is inadequate because of natural differences of stream types and vegetation communities within the study catchments. In contrast, the Fitzroy River trial used reference conditions at a bioregional scale. Although the results from the Fitzroy River appear to be more representative of site conditions, further investigation of the natural variability in vegetation communities and reference conditions is required to further develop the fringing zone theme. In addition, the large size of the catchment questions the validity of using on-ground assessment at a small number of sites. Scores presented here should therefore be interpreted with caution until suitable reference conditions are determined.

Table 8.51:Three examples of adjusting fringing zone scores for reference sites with contrasting bank features.*

Site no.	GA04			KA03			KA05		
Name	Green Ant Creek			Katherine River			Katherine River		
Stream order	2nd order			3rd order			2nd order		
Description	Narrow channel with small clay banks			Wide channel with large sandy banks			Variable channel width with bedrock banks		
	Raw score	Multiplier	FARWH	Raw score	Multiplier	FARWH	Raw score	Multiplier	FARWH
Spatial integrity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Nativeness	0.76	1.00	0.76	0.96	1.00	0.96	1.00	1.00	1.00
Structural integrity	0.50	2.00	1.00	0.20	5.00	1.00	0.30	3.33	1.00
Age structure	0.81	1.23	1.00	0.81	1.23	1.00	0.12	8.33	1.00
Debris	0.90	1.11	1.00	0.96	1.04	1.00	0.32	3.13	1.00
FARWH fringing zone theme score (average of above)	0.79		0.95	0.79		0.99	0.55		1.00

*** Raw scores (0–1) are the unaltered DEWHA riverine vegetation subindices derived from TRARC indicator scores. These scores are scaled up (multiplier) to equal 1.00, except for the nativeness subindex, which is defined as 'reference condition = no weeds'. Raw scores from test sites could be scaled up using multipliers from a matching stream type. Scores exceeding 1.00 should be capped. It remains undetermined what stream types are present in the study catchments and whether appropriate reference sites exist. These examples are provided as a guide for future development using more detailed stream classifications and appropriate reference sites for each stream order.**

Figure 8.21: Photographs of three reference sites used as examples in Table 8.51 (left: GA04, middle:, KA03, right: KA05).

8.5 Literature cited

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9 Aquatic biota theme

9.1 Introduction

The aquatic biota theme consists of three subindices: 1) macroinvertebrates; 2) fish; and 3) aquatic weeds. A fourth index, river metabolism, was investigated as a potential aquatic biota attribute, and is reported in Chapter 11, 'Testing of indicators to disturbance', but was not developed to a stage where it could be used to provide a FARWH score.

The aquatic biota theme is intended to represent the response of biota to changes in environmental conditions (NWC 2007). The macroinvertebrate and fish subindices were trialled, based on field samples, and scores were calculated using an observed/expected (O/E) ratio. Exotic species of fish and aquatic macrophytes were also recorded as present/absent from field observations. Although no exotic fish or aquatic weed species were observed during the field trials in the Daly or Fitzroy river catchments, they have been retained in the methodology to allow comparability of future FARWH assessments if introductions of exotic species occur. Their inclusion also serves to highlight their potential impact on river health. This chapter aims to describe field sampling techniques for each subindex and the integration of these indices to the aquatic biota theme, and to identify challenges associated with applying these methods.

9.2 Methods

9.2.1 Macroinvertebrate subindex

The macroinvertebrate subindex score is based on an O/E ratio calculated using state and region-specific AUSRIVAS models. AUSRIVAS is a rapid assessment tool for measuring river condition, using a series of simple predictive models that compare the macroinvertebrate fauna occurring at a river site with those expected at reference sites (Gray and Hosking 2003).

The model requires data on the macroinvertebrate taxa present at test sites and incorporates environmental variables (the predictor variables) to derive an expected macroinvertebrate assemblage at suitable and comparable reference sites. This technique assumes that an unimpacted test site will support similar macroinvertebrate families to an appropriate reference site. This comparison results in an O/E score, which is a measure of the ecological condition of the site. If O/E = 1, the test site contains the same taxa as undisturbed sites with the same stream characteristics and is assumed to be in good condition. If O/E <1, families are missing and therefore the site is assumed to be degraded to some extent.

An AUSRIVAS model has been developed for the Northern Territory that allows prediction of macroinvertebrate assemblages at the genus, rather than family level. For the Fitzroy catchment, the existing AUSRIVAS model predicts family level assemblages. A brief description of the variation in field methods required for each of these catchment models is provided below.

Macroinvertebrates: Daly River

Macroinvertebrate samples were collected within the Daly River catchment between late June and late August 2009. Samples were collected in accordance with the protocols for the NT AUSRIVAS Early Dry Edge genus model (Lamche 2007). This model is more sensitive to land use and metal pollution than the family-level model (Lamche and Fukuda 2008).

Benthic samples were collected from the channel edge using a net and rake and preserved in the field. In the laboratory, samples were rinsed using a 500 µm sieve and placed in a multicell subsampler. Subsamples were selected randomly and sorted under a stereomicroscope and a channelled sorting tray to obtain a minimum sample of 200 organisms. Chironomid larvae were mounted in Hoyer's fluid and examined at high magnification using an Olympus Vannox microscope. Most specimens were identified to genus level, using regional taxonomic keys.

Five predictor variables are required for the NT AUSRIVAS Early Dry Edge genus model. These were either directly measured in the field or estimated for each site (Table 9.1).

Table 9.1:Five predictor variables for the revised Darwin–Daly region genus level model.

Predictor variable	Method
Catchment area	Estimated catchment area in km^2
Log alkalinity	log_{10} (Alkalinity mg/L + 1)
Stream order	Strahler system from 1: 250K topographic maps.
Standard deviation of elevation	Calculated from SRTM-Oz 3 second DEM using ArcGIS
Average velocity	Habitat water velocity (m/s)

Macroinvertebrates: Fitzroy River

Macroinvertebrates were collected from sites distributed throughout the Fitzroy River catchment, between July and September 2009. This timing coincided (as far as practicable) with the dry season or spring base-flow period, September–October, which is recommended for sampling in this region. Samples were collected from 'channel' habitats following the WA AUSRIVAS sampling protocol (*sensu* Halse et al. 2001).

Benthic samples were collected using a kick-sampling technique with a long-handled (1.5 m long) pond net (250 um mesh; 350 by 250 mm opening, 50–75 cm depth). All samples were standardised to an area of 10 m^2 that represented the variety of habitats available to aquatic fauna (e.g. substratum and leaf packs) in both the main channel and littoral habitats. Netted samples were washed, sieved into size fractions, live-picked in the field for 60 minutes and preserved in 70% alcohol. In the laboratory, macroinvertebrates were identified to family level with the exception of Chironomids (subfamily), oligochaetes and acarinids (order). Microcustracea, including ostracods, copepods and cladocerans, were recorded but are not used in the northern WA model.

Five predictor variables were required for the WA spring–channel model in order to assign appropriate reference sites (Table 9.2). A range of catchment and local-scale environmental variables were also estimated or measured for each site, based on field data sheets provided in Halse et al. (2001). Although the majority of this data was not required for the AUSRIVAS modelling it was recorded to help increase the knowledge of macroinvertebrate distributions in the Kimberley and in the event that it may be useful for future refinement of existing models.

Table 9.2: Five predictor variables for the Western Australian spring–channel model.

Predictor Variable	Method
Discharge	Mean annual discharge in mega-litres per annum
Latitude	Latitude of site (decimal degrees to 4dp)
Longitude	Longitude of site (decimal degrees to 4dp)
Rainfall	Mean annual rainfall (mm)
Velocity	Log 10 [x cm/sec] maximum. Flow Velocity in habitat

For AUSRIVAS, it is possible for sites to achieve a score greater than 1.0. Based on the limited understanding of macroinvertebrate distributions, a decision was made to ‘cap’ scores at 1.0—i.e. test sites with a greater number of macroinvertebrate species compared to reference sites (O/E >1.0) were capped at 1.0 and not scaled lower to reflect any difference from ‘expected’.

9.2.2 Fish subindex

The composition of native species in degraded stream reaches is likely to differ from that expected in undisturbed streams of similar type (Kennard et al. 2006 and references therein). A comparison of fish species composition (presence/absence) predicted to occur on the basis of environmental features, with the species actually present at a site can provide an indication of the health of the fish community. The ratio of the observed number of species (O) to the expected number of species (E) can be used as a summary of ecosystem health on the basis of native fish species composition (indicator hereafter termed fish assemblage O/E).

The fish subindex is comprised of two components: 1) an observed/expected (O/E) ratio of fish species, and 2) an exotic fish presence/absence score. The two components are averaged to derive a fish subindex score for the site (Equation 9.1).

Equation 9.1

$$F = (OE * 0.5) + (EX * 0.5)$$

where:
F = fish subindex score for a site (0–1)
OE = observed:expected fish species ratio (0–1)
EX = exotic fish score (0–1).

A range of other possible fish indices was also evaluated including the Index of Biotic Integrity and methods associated with the Sustainable Rivers Audit, and Index of Stream Condition. Many of these indices required specific ecological knowledge to assign species to trophic, habitat or reproductive guilds. Quantitative knowledge of this kind is generally insufficient to apply similar indices to fish assemblages in the Daly and Fitzroy river catchments. Fish O/E models are at different stages of development for the two study catchments and an outline of the methods for each catchment are given below.

Fish O/E: Daly River

Fish assemblage data was recorded from sites in the Daly River between June and September 2009 in wadeable streams (Appendix 13.8). Full details on the sampling methodology and evaluation of the accuracy, precision and efficiency of the sampling protocol are presented in Kennard et al. (2009 a,b).

Within each selected sampling site, fish assemblages were sampled by electrofishing (boat and/or backpack) at multiple discrete locations within each site. These samples are hereafter termed electrofishing 'shots' with each shot fixed at five minutes duration (elapsed time). At least 10 electrofishing shots were usually undertaken at each site as this level of effort provided reasonable estimates of local fish assemblages (Kennard et al. 2009b). Replicate measures of a range of hydraulic and microhabitat parameters were taken for each shot. Fish collected from each electrofishing shot were identified to species level, counted and returned to the approximate point of capture.

The numbers of species caught or observed were compared to 'expected' species richness developed from modelled data to produce an O/E score. See Appendix 13.7, 'Fish modelling in the Daly River catchment.'

Fish O/E: Fitzroy River

No predictive model was available for the Fitzroy catchment. Instead, the fish species expected to occur at each site were derived from the literature, recent unpublished fish surveys and expert opinion. Nonetheless, the collection methods used are consistent with the approach described in Kennard et al. (2009) and include quantitative information on in-stream structural habitat, which will allow for the development of predictive models in future river health assessments in the catchment.

Fish assemblage data was recorded from sites, distributed throughout the catchment, between July and September 2009. Fish were sampled using a variety of non-destructive techniques, including, boat and backpack electrofishing and fyke netting. In larger waterholes, fish were collected, using a purpose-built 4.5 m electrofishing boat fitted with a Smith-Root Inc.™ (Vancouver WA., USA) 5 kW generator-powered pulsator. In smaller water holes, waterholes with difficult access and shallow riffle habitats, fish were collected using a Smith-Root Inc.™ (Vancouver WA., USA) backpack electrofisher (Model LR-24; 24V 400W), either from a small punt (<3.0 m) (in pools) or by wading (in shallow habitats).

For sites comprising a variety of deep and shallow water habitats, electrofishing techniques were interchanged (e.g. backpack and boat-mounted) to sample a representative range of habitats. When various electrofishing techniques were employed at a site, they were used in proportion to the availability of suitable habitats for each technique. For sites comprising small but non-wadeable pools (where the boat electrofisher could not be launched), fish were sampled, using both the backpack electrofisher (from a small punt) and a combination of fine (5 mm) and coarse (10 mm) mesh fyke nets to maximise the likelihood of collecting a representative sample of fish species.

At each site, up to 10 electrofishing shots were conducted following the protocols described in Kennard et al. (2009). Individual shots comprised 5 minutes of elapsed fishing time (i.e. sample length not prescribed) and were conducted across the range of representative in-stream habitats at each site. The major habitat types at each site were sampled at least once and then the remaining sampling effort focused on the most abundant habitat types.

Habitats within a site were defined by hydraulic and structural habitat criteria such as riffles, runs, pools, macrophyte beds, stretches of mid-channel open water, undercut banks, woody debris piles etc. To maintain independence between electrofishing shots, the location of shots was selected using the following criteria:

- In wide streams (>15m), shots are conducted on alternate banks.
- Mid-channel shots were spaced at least 25m away from the preceding shot.
- In narrower streams (<15m) electrofishing was conducted in a zigzag pattern, incorporating both mid-channel and littoral habitats and shots were spaced at least 25 m away from the previous shot.

Sample processing

All fish collected were immediately placed in a 100 L aerated holding tank. All fish were identified, enumerated and a subsample was measured for length (standard length SL, mm) and weight (W, g). All fish were returned to the water alive at their point of capture. Subsampling followed the protocols described by Kennard et al. (2009).

Environmental data

A range of catchment and local-scale environmental variables was estimated for each site following a modified protocol described by Kennard et al. (2009). This data was collected to facilitate future development of a predictive model of fish assemblages in the Fitzroy River catchment. The model would allow future assessments to incorporate a quantitative prediction of the species expected to occur into the O/E ratio for each site. Environmental variables were recorded in the field under the following broad categories: water chemistry, substrate composition, structural habitat and hydraulic biotype.

A detailed description of the environmental parameters measured and the methods used to quantify this data is provided in Appendix 13.7, ‘Fish modelling in the Daly River catchment’.

Data analysis

In order to produce an O/E score for fish, a list of expected fish species was produced for each site, based on a review of available literature. An analysis of datasets from Allen (1975), Morgan et al. (2005), Thorburn et al. (2004), and Wharf and Pettit (pers comm. 2008) produced a table of expected species for each region that was then refined for each site based on expert opinion and knowledge of the catchment.

The observed list generated in the field was then compared to this expected list to produce an O/E score, which is a measure of the ecological condition of the site. If O/E = 1, the test site contains the same families as undisturbed sites with the same stream characteristics and is assumed to be in good condition. If O/E <1, families are missing and therefore the site is assumed to be degraded to some extent.

Two O/E fish scores were calculated for the Fitzroy River catchment.

1) ‘Raw O/E’—As the O/E score accounts for reference condition by providing an expected species list (i.e. reference) for each site, an O/E score not standardised to selected reference sites within the catchment was calculated.
2) ‘Standardised O/E’—The fish index was also presented as a standardised (to reference sites) score for reasons identified in the discussion of this chapter (Section 9.4). O/E

scores for test sites were scaled against reference condition, which scored 1.0, to produce a standardised O/E ratio. Reference sites were chosen for each of the subregions of the Fitzroy following procedures outlined in Chapter 3.4.2.

Scores for nonreference sites were then ground-truthed, using expert opinion and scoring bands that indicate departure from natural (*sensu* Sustainable Rivers Audit). This was used to account for any issues not addressed by the three attributes measured (e.g. presence of rare and threatened fauna). Fish assemblage structure was described (also subjectively assessed) as a departure from natural with 0 to 0.2 described as 'extreme modification'; 0.2–0.4 as 'major modification'; 0.4–0.6 as 'moderate modification'; 0.6–0.8 as 'minor modification'; and 0.8–1 as 'at or near natural condition'. It should be noted, however, that the boundaries for these classes do not represent any known thresholds in river condition and rigid categories can lead to misleading interpretations when considering values near the boundary cutoffs (i.e. 0.59 and 0.61 fall in different classes but would not represent different fish community health). As such, the process of ground-truthing calculated scores was only used to modify index scores if necessary.

Based on the limited understanding of fish distributions, a decision was made to cap scores at 1.0—i.e. test sites with more fish species compared to reference sites (O/E >1.0) were capped at 1.0 and not scaled lower to reflect any difference from 'expected'.

Exotic fish

This is a measure of presence of exotic fish species. In both the Daly and Fitzroy river catchments, the presence of introduced fish was noted during the general fish surveys (see methods above). For each site, presence or absence of exotic fish were scored 0 or 1, respectively.

9.2.3 Aquatic weeds subindex

Opportunistic observation of aquatic vegetation was undertaken in both the Daly and Fitzroy river catchments. In both catchments, knowledge on aquatic weed species, their identification and distribution is limited. Where possible, aquatic weeds were identified as either native or exotic, based on field identification and local knowledge. For each site, presence or absence of aquatic weeds was scored 0 or 1, respectively.

9.2.4 Aggregation and integration

For each of the three subindices (macroinvertebrates, fish and aquatic weeds) site scores were averaged for each stream order and weighted for contributing length of total stream network to produce a SWMA subindex score (Equation 9.2).

Equation 9.2

$$SI = ((L_{S1} / L_{SN} * SI_{S1}) + (L_{S2} / L_{SN} * SI_{S2}) + \ldots)$$

where:
SI = *subindex SWMA score for either a) macroinvertebrates, b) fish or c) aquatic weeds (0–1)*
L_{S1} = *combined length of all 1st order streams* (L_{S2} = *2nd order etc.)*
L_{SN} = *total length of entire stream network*
SI_{S1} = *average subindex score for 1st order streams* (SI_{S2} = *2nd order, etc.) for either a) macroinvertebrates, b) fish or c) aquatic weeds.*

For the Daly River SWMA, where scores have been aggregated to a stratified zone (developed and undeveloped), an additional integration step was used to compute each subindex and final aquatic biota theme score. For each subindex (macroinvertebrates, fish and aquatic weeds), zone scores are weighted by contributing stream length to the total SWMA perennial network: developed zone = 747 km (47%) of perennial streams; undeveloped zone = 840 km (53%) of perennial streams (Equation 9.3).

Equation 9.3

$$SI = (SI_D * 0.47) + (SI_U * 0.53)$$

where:
SI = *subindex score for the Daly River SWMA (0–1)*
SI_D = *subindex score for the Daly River developed zone (0–1)*
SI_U = *subindex score for the Daly River undeveloped Zone (0–1).*

The SWMA subindex scores were then integrated to produce an aquatic biota theme score using Equation 9.4. The macroinvertebrate and fish subindices were given equal weighting (40% each), with the aquatic weeds subindex assigned a lower weighting (20%), as field results were derived from opportunistic observations and basic assumptions.

Equation 9.4

$$AB = (MI * 0.4) + (F * 0.4) + (AW * 0.2)$$

where:
AB = *aquatic biota theme score for the SWMA (0–1)*
MI = *macroinvertebrate subindex score for the SWMA (from Equation 9.2)*
F = *fish subindex score for the SWMA (from Equation 9.2)*
AW = *aquatic weeds score for the SWMA (from Equation 9.2).*

9.3 Results

9.3.1 Daly River catchment: macroinvertebrate subindex

The mean O/E score for 41 sites in the Daly River catchment was 0.83 ± sd 0.12, and ranged between 0.52 and 1.09. Twenty sites were classified band A (i.e. equivalent to reference condition), 19 sites were classified as not equivalent to reference. Final macroinvertebrate subindex scores were 0.83 and 0.86 for the developed and undeveloped zones in the Daly catchment respectively (Table 9.3).

Table 9.3: Computation of the macroinvertebrate subindex score for Daly River stratified zones, using stream-order length weightings (from Equation 7.119.3): a) developed zone, and b) undeveloped zone. Scores are between 0–1.

(a) Developed zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Zone-weighted score (W*A)
1st	243(32%)	0.32	26	13	0.78	0.25
2nd	184(25%)	0.25	21	11	0.87	0.22
3rd	127(17%)	0.17	16	4	0.83	0.14
4th	68(9%)	0.09	6	2	0.85	0.08
5th	125(17%)	0.17	7	2	0.84	0.14
Total sub-SWMA	747		76	32 (42%)		**0.83**

(b) Undeveloped zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Zone weighted score (W*A)
1st	258(31%)	0.31	17	2	0.86	0.27
2nd	195(23%)	0.23	17	2	0.89	0.20
3rd	209(25%)	0.25	24	2	0.86	0.21
4th	52(6%)	0.06	4	1	0.78	0.05
5th	126(15%)	0.15	11	1	0.88	0.13
Total sub-SWMA	840		73	8 (11%)		**0.86**

9.3.2 Daly River catchment: fish subindex

In 2009, 23 sites were surveyed in the Daly River catchment using electrofishing techniques (Figure 9.1). Twenty-three species were caught or observed, with the most frequently encountered species—Spangled grunter *Leiopotherapon unicolor*, western rainbowfish *Melanotaenia australis* and purple-spotted gudgeon *Mogurnda mogurnda* (Table 9.4). Species richness per site ranged between four and 17, resulting in O/E site scores between 0.47 and 0.94 (Table 9.5).

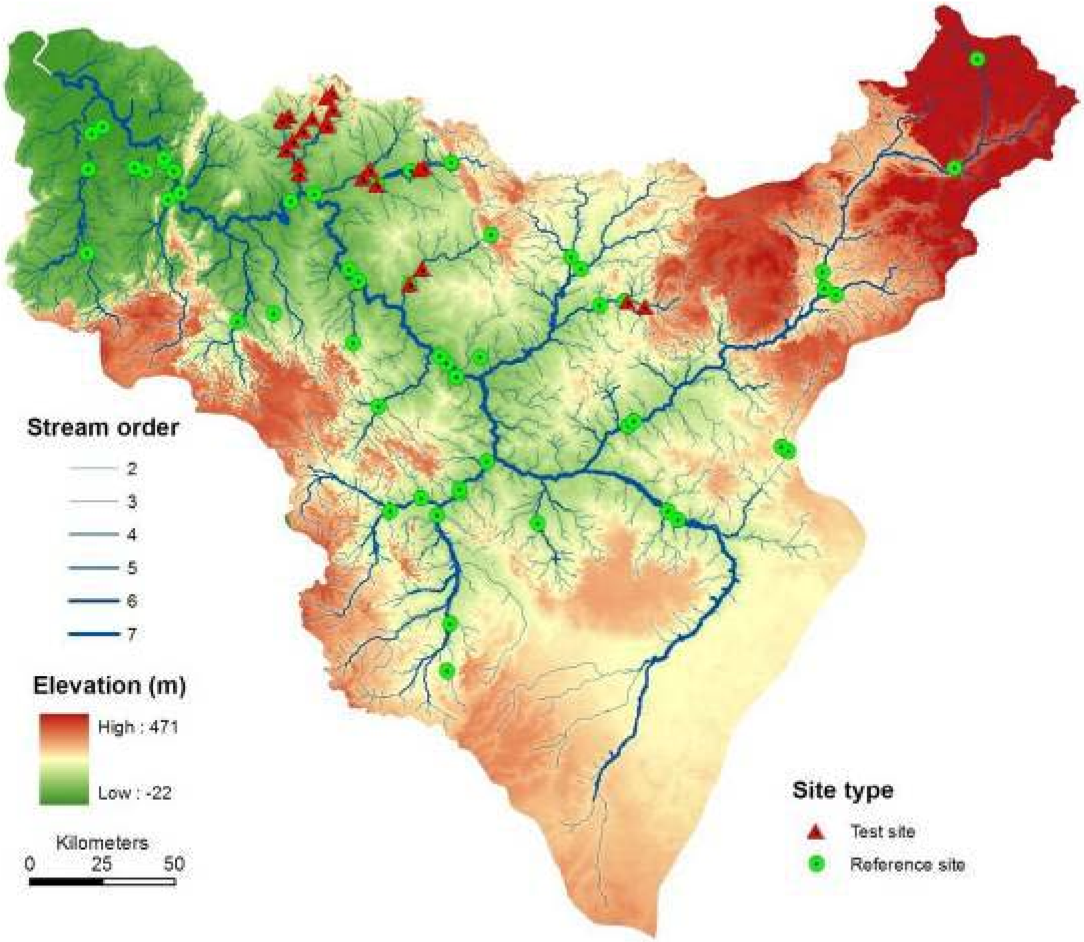

Figure 9.1: Location of reference and test sites in the Daly River catchment, Northern Territory.

Table 9.4: List of fish species sampled at 23 sites in the Daly River catchment, July–Sept. 2009.

Common name	Scientific name	Freq	%freq
Spangled grunter	*Leiopotherapon unicolor*	23	100.0
Western rainbowfish	*Melanotaenia australis*	22	95.7
Purple-spotted gudgeon	*Mogurnda mogurnda*	22	95.7
Strawman	*Craterocephalus stramineus*	19	82.6
Sooty grunter	*Hephaestus bancrofti*	18	78.3
Mouth almighty	*Glossamia aprion*	16	69.6
Eel-tailed catfish	*Neosilurus hyrtlii*	13	56.5
Banded grunter	*Amniataba percoides*	11	47.8
Golden goby	*Glossogobius aureus*	11	47.8
Black catfish	*Neosilurus ater*	10	43.5
Giant goby	*Oxyeleotris selheimi*	10	43.5
Barramundi	*Lates calcarifer*	8	34.8
Glass fish	*Ambassis* sp.	7	30.4
Tarpon	*Megalops cyprinoides*	5	21.7
Bony bream	*Nematalosa erebi*	5	21.7
Sleepy cod	*Oxyeleotris lineolatus*	5	21.7
Long-tom	*Strongylura kreffti*	5	21.7
Archer fish	*Toxotes chatareus*	5	21.7
Sharp-nosed grunter	*Syncomistes butleri*	4	17.4
Fork-tailed catfish	*Arius graeffei*	2	8.7
Freshwater sole	*Leptachirus triramus*	2	8.7
Freshwater mullet	*Liza ordensis*	2	8.7
Black-banded rainbowfish	*Melanotaenia nigrans*	1	4.3

Table 9.5: O/E scores for 23 sites in the Daly River catchment, July–Sept. 2009.

Site	obser-ved	expected	O/E	Site	obser-ved	expected	O/E
DG-01	6	11.69	0.513	GT-03	4	5.70	0.701
DG-02	9	12.20	0.738	GT-04	5	7.53	0.664
DP-01	7	7.99	0.877	HY-01	11	14.68	0.750
ED-01	8	9.73	0.822	HY-02	6	6.73	0.892
ED-01X	5	4.57	1.094	MD-01	11	11.66	0.943
GA-01	5	7.70	0.649	SN-01	5	7.23	0.692
GA-02	4	8.40	0.476	SN-02	5	8.67	0.577
GA-03	5	7.63	0.655	SN-03	4	8.04	0.497
GA-04	7	12.24	0.572	SN-04	3	5.03	0.596
GA-05	9	16.12	0.558	SN-05	9	11.72	0.768
GT-01	4	6.87	0.583	ST-01	10	13.87	0.721
GT-02	4	8.56	0.467	ST-02	7	13.35	0.524

There were no exotic fish present within the Daly catchment and therefore all sites scored a value of 1.0 for exotic fish. Using 9.3, final fish subindex scores for the Daly developed and undeveloped zones were **0.64** and **0.96** respectively (Table 9.6).

Table 9.6: Computation of the fish subindex score for Daly River stratified zones using stream order length weightings (from Equation 7.11 9.3): a) developed zone, and b) undevelopedzZone. Scores are between 0–1.

(a) Developed zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Zone-weighted score (W*A)
1st	243(32%)	0.43	26	12	0.68	0.29
2nd	184(25%)	0.34	21	9	0.64	0.21
3rd	127(17%)	0.23	16	1	0.56	0.13
4th	68(9%)	No data	6	0	no data	no data
5th	125(17%)	No data	7	0	no data	no data
Total sub-SWMA	747 km	1.00	76	22 (29%)		**0.64**

(b) Undeveloped zone

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Zone-weighted score (W*A)
1st	258(31%)	1.00	17	1	0.96	0.96
2nd	195(23%)	No data	17	0	No data	No data
3rd	209(25%)	No data	24	0	No data	No data
4th	52(6%)	No data	4	0	No data	No data
5th	126(15%)	No data	11	0	No data	No data
Total sub-SWMA	840	1.00	73	1(1%)		**0.96**

9.3.3 Daly River catchment: aquatic weeds subindex

There were no aquatic weeds recorded at the sampling sites within the Daly River catchment. Therefore, both the developed and undeveloped zones scored **1.0.**

9.3.4 Daly River catchment: integration

Using Equations 9.3 and 9.4, macroinvertebrates, fish and aquatic weeds scores were integrated to give a final aquatic biota theme score of 0.79 and 0.93 for the Daly developed and undeveloped zones, and **0.86** for the Daly River SWMA (Table 9.7).

Table 9.7: Integration of the macroinvertebrate, fish and aquatic weeds subindices to produce a final aquatic biota theme score for the Daly River developed and undeveloped zones, and the Daly River SWMA, using Equations 9.3 and 9.4.

SWMA	Macroinvertebrates subindex (40%)	Fish subindex (40%)	Aquatic Weeds subindex (20%)	Aquatic biota theme
Developed	0.83	0.64	1.00	**0.79**
Undeveloped	0.86	0.96	1.00	**0.93**
Daly River	0.85	0.81	1.00	**0.86**

9.3.5 Fitzroy River catchment: macroinvertebrate subindex

Macroinvertebrates were sampled at 21 sites that were geographically spread across the three Fitzroy River subregions. Nine sites were located on small tributaries, 10 sites were sampled from the middle region and two from the upper catchment.

AUSRIVAS scores were calculated for 21 sites in the Fitzroy River SWMA (1.6 % of the 1191 FARWH reaches). Two macroinvertebrate sites were outside the range of the AUSRIVAS model (i.e. no suitable reference site was available) and were therefore excluded, reducing the number of sample sites to 19. Nine sites were classified band A (i.e. equivalent to reference condition) and 10 were classified as not equivalent to reference. Scores for each stream order were averaged and weighted using Equation 9.2 to produce a Fitzroy River SWMA macroinvertebrate score of **0.87** (Table 9.8).

Table 9.8: Computation of the macroinvertebrate subindex score for the Fitzroy River SWMA using stream-order length weightings (from Equation 9.2).

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average score	Weighted score (W*A)
1st	5904 (50%)	0.50	600	3	0.88	0.44
2nd	2813 (24%)	0.24	261	2	0.90	0.21
3rd	1872 (16%)	0.16	201	2	0.85	0.13
4th	632 (5%)	0.05	71	2	0.84	0.04
5th	225 (2%)	0.02	23	5	0.76	0.01
6th	454 (4%)	0.04	35	5	0.74	0.03
Total SWMA	11 00 km	**1**	1191	19 (1.6%)		**0.87**

9.3.6 Fitzroy River Catchment: fish subindex

Fish were sampled from 22 sites in the Fitzroy River SWMA (1.8 % of the 1191 FARWH reaches) that were geographically spread across the three subregions. Five sites were located in the lower reaches of the Fitzroy River main channel (including the Cunningham River anabranch), between Fitzroy Crossing and Camballin Barrage, and one site was located on a lower-catchment tributary. Three sites were sampled on the lower reaches of the Margaret River and an additional site was sampled on the Leopold River. A further three main channel sites were located between Fitzroy Crossing and Mornington Station, with the remaining sites located in the lower reaches of mid-catchment tributaries, including the Adcock, Hann and Traine rivers. This distribution of sites resulted in nine sites located on small tributaries, nine from the middle Fitzroy River region and four from the upper regions of the catchment. Twenty-two species were collected in the field surveys, with all species previously known to occur in the catchment (Table 9.9).

Table 9.9: The sites within the Fitzroy River catchment in which different fish species were captured during the FARWH field trials from July to September 2009.

Fish species	Site number	Total sites
AMBASSIDAE		
Glassfish: *Ambassis* sp1	6, 9–10, 12, 21, 24, 28, 32–33	9
Glassfish: *Ambassis* sp2	12	1
ANGUILLIDAE		
Indian shot-finned eel: *Anguilla bicolor*	32	1
APOGONIDAE		
Mouth almighty: *Glossamia aprion*	6, 9–10, 12, 17, 26, 32, 34	8
ARIIDAE		
Lesser salmon catfish: *Arius graeffei*	1-2, 4, 6–7, 9-10,12, 17, 20 26, 29–30, 32	14
ATHERINIDAE		
Prince Regent hardyhead: *Craterocephalus lentiginosus*	6, 10, 12, 17, 26, 32	6
BELONIDAE		
Freshwater longtom: *Strongylura krefftii*	1–2, 9, 12, 17, 30, 32	7
CENTROPOMIDAE		
Barramundi: *Lates calcarifer*	1, 6, 12, 17, 29, 30	6
CLUPEIDAE		
Bony bream: *Nematalosa erebi*	1, 4, 6–7, 9–10, 12, 17, 21, 26, 28–30, 32–33	15
ELEOTRID		
False-spotted gudgeon: *Mogurnda oligolepis*	24	1
Giant gudgeon: *Oxyeleotris selheimi*	1, 3, 6, 24, 26, 28, 32–34	9
ELOPIDAE		
Oxeye herring (Tarpon): *Megalops cyprinoides*	4, 10, 12, 17, 29–30	6
GOBIIDAE		
Flathead goby: *Glossogobius giurus*	1–3, 5–7, 17, 21, 24, 26, 28–34	17
MELANOTAENIIDAE		
Western rainbowfish: *Melanotaenia australis*	1–3, 6, 10, 17, 20–21, 24, 28–34	16
PLOTOSIDAE		
Toothless catfish: *Anodontiglanis dahli*	2, 9	2
Black catfish: *Neosilurus ater*	1, 6–7, 9, 29	5
Hyrtl's tandan: *Neosilurus hyrtlii*	3, 10, 20, 24, 28, 30–33	9
False-spined catfish: *Neosilurus pseudospinosus*	31–32	2
TERAPONIDAE		
Jenkin's grunter (Black bream): *Hephaestus jenkinsi*	1–7, 9, 12, 17, 21, 24, 26, 29–34	19
Spangled perch: *Leiopotherapon unicolor*	1–7, 9–10, 12, 17, 20–21, 24, 26, 28–34	22

Greenway's grunter: *Hannia greenwayi*	3, 6–7, 12, 17, 20–21, 26, 29–32	12
Barred grunter: *Amniataba percoides*	2, 4–7, 9–10, 17, 21, 26, 31–34	14
TOXOTIDAE		
Archerfish: *Toxotes* sp.	1, 4, 6–7, 9–10, 12, 17, 21, 29–33	14

Species richness per site ranged between four and 16, resulting in O/E site scores between 0.17 and 1.0 (Table 9.10). There were no exotic fish present within the Fitzroy catchment and therefore all sites scored a value of 1.0 for exotic fish.

Table 9.10: O/E scores for 23 sites in the Fitzroy River catchment, July–Sept. 2009.

Site	Sub-region	Order	Observed	Expected	Native O/E sub-index	Exotic sub-index	Raw O/E	Standardised O/E (scaled to reference and capped)
FARWH_17	M	4	14	20	0.700	1	**0.85**	**1.00**
FARWH_6	M	5	16	25	0.640	1	**0.82**	**0.99**
FARWH_7	M	5	10	23	0.435	1	**0.72**	**0.83**
FARWH_1	M	6	11	26	0.423	1	**0.71**	**0.82**
FARWH_12	M*	6	15	23	0.652	1	**0.83**	**1.00**
FARWH_2	M	6	10	26	0.385	1	**0.69**	**0.79**
FARWH_4	M	6	7	26	0.269	1	**0.63**	**0.71**
FARWH_5	M	6	4	23	0.174	1	**0.59**	**0.63**
FARWH_9	M	6	11	25	0.440	1	**0.72**	**0.84**
FARWH_10	S	1	11	20	0.550	1	**0.78**	**0.92**
FARWH_24	S	1	8	21	0.381	1	**0.69**	**0.79**
FARWH_3	S	1	7	18	0.389	1	**0.69**	**0.80**
FARWH_34	S	1	8	17	0.471	1	**0.74**	**0.86**
FARWH_28	S	2	7	16	0.438	1	**0.72**	**0.84**
FARWH_33	S	2	11	17	0.647	1	**0.82**	**1.00**
FARWH_30	S*	3	13	20	0.650	1	**0.83**	**1.00**
FARWH_32	S	3	17	17	1.000	1	**1.00**	**1.00**
FARWH_31	S	4	9	19	0.474	1	**0.74**	**0.86**
FARWH_20	U	4	6	19	0.316	1	**0.66**	**0.83**
FARWH_21	U	4	9	20	0.450	1	**0.73**	**0.97**
FARWH_26	U	5	11	22	0.500	1	**0.75**	**1.00**
FARWH_29	U*	5	10	21	0.476	1	**0.74**	**1.00**

*reference sites

Using Equation 9.2, the final scores for the fish subindex for the Fitzroy SWMA were **0.76** and **0.87,** using raw and standardised fish O/E scores of respectively (Table 9.11).

Table 9.11:Computation of the fish subindex score for the Fitzroy River SWMA, using stream-order length weightings (from Equation 9.2) for a) raw O/E scores, and b) standardised O/E scores.

(a) Using raw O/E fish scores

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Weighted score (W*A)
1st	5904 (50%)	0.50	600	4	0.72	0.36
2nd	2813 (24%)	0.24	261	2	0.77	0.18
3rd	1872 (16%)	0.16	201	2	0.91	0.14
4th	632 (5%)	0.05	71	4	0.74	0.04
5th	225 (2%)	0.02	23	4	0.76	0.01
6th	454 (4%)	0.04	35	6	0.69	0.03
Total SWMA	11 900 km	1.00	1191	22 (1.8%)		**0.76**

(a) Using standardised (to reference) O/E fish scores

Stream order	Stream length (km)	(W) Weighting (% of total length)	No. of reaches	No. of sample reaches	(A) Average O/E score	Weighted score (W*A)
1st	5904 (50%)	0.50	600	4	0.84	0.42
2nd	2813 (24%)	0.24	261	2	0.92	0.22
3rd	1872 (16%)	0.16	201	2	0.87	0.14
4th	632 (5%)	0.05	71	4	0.91	0.05
5th	225 (2%)	0.02	23	4	0.95	0.02
6th	454 (4%)	0.04	35	6	0.79	0.03
Total SWMA	11900 km	1.00	1191	22(1.8%)		**0.87**

9.3.7 Fitzroy River Catchment: aquatic weeds subindex

There were no aquatic weeds recorded at the sampling sites within the Fitzroy catchment and therefore the aquatic weeds score for the Fitzroy SWMA was 1.

9.3.8 Fitzroy River catchment: integration

Using Equation 9.4, macroinvertebrates, fish and aquatic weeds scores were integrated to give a final aquatic biota theme score of **0.90** and **0.85**, using the standardised and raw fish O/E scores, respectively (Table 9.12).

Table 9.12: Integration of the macroinvertebrate, fish and aquatic weeds subindices to produce a final aquatic biota theme score for the Fitzroy River SWMA, using

Equation 9.4.

SWMA	Macroinvertebrates subindex (40%)	Fish subindex (40%)	Aquatic weeds subindex (20%)	Aquatic biota theme
Fitzroy	0.87	0.87 (reference standardised)	1.00	**0.90**

Fitzroy	0.87	0.76 (raw)	1.00	**0.85**

9.4 Discussion

As with other themes, the aquatic biota theme experienced a number of limitations relating to site and reference condition selection, i.e. sites were restricted to areas of the catchment that had surface water present during the dry season and sites were disproportionally spread across the catchment and across stream orders. A discussion of each subindex is given below.

Macroinvertebrates

AUSRIVAS models used in the Daly and the Fitzroy river catchments required different sampling methods (e.g. preservation versus live pick; and genus versus family), and may therefore have different sensitivities. In the Daly River catchment, results for both developed and undeveloped zones were similar (0.83 and 0.86 respectively), suggesting that either the model or the macroinvertebrate taxa in the Daly River catchment are not sensitive enough to pick up moderate levels of disturbance (see Chapter 11, 'Testing of indicators to disturbance'). However, the macroinvertebrate scores for the Daly River SWMA were higher than the macroinvertebrate subindex scores recorded in the more-developed Darwin Harbour SWMA: 0.65 (Dixon et al. 2009).

The macroinvertebrate subindex score for the Fitzroy (0.87) was similar to results for the Ord River (0.83) (Dixon et al. 2009). Surveys conducted as part of The Monitoring River and Health Initiative (MRHI) showed that the Ord and the Fitzroy have the greatest disturbance in the Kimberley, with values classified in the AUSRIVAS significantly impaired band score. They proposed that these values were a result of cattle grazing. Severe erosion caused by cattle grazing was evident on parts of the Ord catchment before the middle of last century, leading to commencement of partial destocking and a rehabilitation program in the 1960s (Fitzgerald 1968). Grazing has also had detrimental effects on the floodplain of the Fitzroy River (Payne et al. 1979). A review of the current macroinvertebrate AUSRIVAS model for the Fitzroy is recommended for future assessments as more comprehensive data and information on reference sites becomes available.

Fish

The strongly nested and hierarchical organisation of river landscapes suggests that aquatic ecosystems are strongly influenced by their surroundings at a variety of scales (Hunsaker and Levine 1995; Allan 2004). Consequently, human impacts on local assemblages are likely to be scale-dependent, potentially being affected by processes operating at both landscape scales (e.g. agricultural runoff from upstream areas and barriers downstream) and local scales (e.g. riparian and in-stream habitat degradation), a concept demonstrated in practice by many studies (e.g. Roth et al. 1996; Allan et al. 1997). That fish can integrate human disturbances arising from multiple sources at a range of spatial and temporal scales is seen as one of the benefits of using fish as indicators. However, the existence of multiple, scale-dependent mechanisms, potentially nonlinear responses of biota to disturbance, and the difficulties of separating current from historical effects, can make it difficult to establish relationships between disturbance and ecosystem health indicators or to diagnose the specific sources or mechanisms of human impact.

In the Fitzroy River FARWH trial, both standardised and nonstandardised (to reference sites) fish indices were presented for several reasons. First, there was substantial uncertainty surrounding the prediction of species expected at each site. In the absence of a numerical model (*sensu* Kennard et al. 2009) an expected species list for each site was derived from existing data on fish distribution in the catchment (see Section 9.2.2 above). As such, these predictions were precautionary (resulting in relatively high numbers of expected species), and reflect broadscale distributional patterns without considering the influence of other environmental conditions on fish presence or absence (e.g. structural habitat etc). Second, considering the wide distributions of many fish species within the catchment, it was important to account for annual variations in these distributions that may result from a variety of natural, antecedent conditions. For example, many fish in the Fitzroy River are either diadromous or potadromous, and their distribution in the catchment is likely to be influenced by the antecedent riverflows that facilitate longitudinal (and lateral) movements within the river. Standardising the fish index scores to reference sites in the year of study accounts for these interannual variations in distribution, as well as uncertainty surrounding the prediction of fish species present at each site. Although the influence of these indices on the final aquatic biota score was relatively minor (range = 0.85 (unstandardised) to 0.90 (reference standardised)), further information on the natural variability of fish distributions, and knowledge on the fish species expected at each site, is required to further refine the methodology presented here.

Distribution of fish sites was designed for testing the sensitivity of fish against a gradient of disturbance. In the Daly River catchment, most fish-sampling was conducted in the developed SWMA and provides an adequate assessment of smaller stream orders (first to third). However, only one site was surveyed in the undeveloped SWMA. Therefore, results for the latter SWMA are difficult to interpret. Sampling was also limited to wadeable streams, and refinement of the existing Daly River model is needed to provide appropriate reference sites for the first-order streams sampled.

Desktop trials

Table 9.13 presents results of the desktop trials of FARWH in the Darwin Harbour and Ord River catchments. Results from this field study are also included; however, care should be taken when comparing scores between SWMAs, as methods used vary greatly (see Dixon et al. 2009).

Table 9.13 Aquatic Biota Theme and subindex scores for all wet/dry tropical FARWH SWMAs.*

SWMA	Macroinvertebrate subindex	Fish subindex	Aquatic Weeds subindex	Aquatic biota theme
Daly River: developed zone	0.83	0.64	1.00	**0.79**
Daly River: undeveloped zone	0.86	0.96	1.00	**0.93**
Fitzroy River	0.87	0.87	1.00	**0.90**
Darwin Harbour	0.65	1.00 (exotic fish)	0.95	**0.70**
Ord River	0.83	0.88	-	**0.85**

*** Desktop trials were conducted in the Darwin Harbour and Ord River catchments using existing data collected in 2005 (Darwin Harbour) and between 1998–2006 (Ord River). Calculation methods of subindex scores varied between trials due to limited data (see Dixon et al. 2009).**

9.5 Literature cited

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10 Theme integration

10.1 Introduction

To provide an overview of river condition, an overall FARWH score was calculated from the six theme scores. Advantages of calculating a final score include the ability to rapidly compare SWMAs across regions and identity those catchments that are close to reference condition or degraded to some degree. Disadvantages of using a final score are that low scoring themes may be masked by themes that score highly. It is therefore critical, especially from a management perspective, that subindex scores also be reported, and considered in the context of the final SWMA score.

10.2 Methods

The six FARWH themes were integrated to give a final score for the SWMA using standardised Euclidean distance (Equation 10.19). This approach to integration follows that agreed at the national FARWH Workshop, 26 February 2009, in Perth.

Equation 10.19

$$FARWH = 1- ((\sqrt{((1-CD)^2 + (1-HD)^2 + (1-WQ)^2 + (1-PF)^2 + (1-FZ)^2 + (1-AB)^2)}) / (\sqrt{6}))$$

where:
FARWH = ***final integrated SWMA score (0–1)***
CD = ***catchment disturbance theme score***
HD = ***hydrological disturbance theme score***
WQ = ***water quality theme score***
PF = ***physical form theme score***
FZ = ***fringing zone theme score***
AB = ***aquatic biota theme score.***

10.3 Results

10.3.1 Daly River SWMA

Integration of the six themes using Equation 10.19 produced a final FARWH score of **0.83** and **0.86** for the developed and undeveloped stratified zones. Theme scores for each zone were aggregated using methods described in each theme chapter of this report (i.e. stream-length weightings, or area weightings). The exception was the hydrological disturbance theme, which was only assessed at the SWMA level (see Chapter 5, ‘Hydrological disturbance theme’). A final FARWH score for the Daly River SWMA was **0.85**. Lowest scores were the catchment disturbance and fringing zone themes (both 0.80). Limitations of methods used to derive these scores are discussed in individual theme chapters of this report.

Table 10.52: Integration of the six FARWH themes to a final FARWH score for the developed and undeveloped zones, and the entire Daly River SWMA using Equation 10.19.

Theme	Developed zone	Undeveloped zone	Daly River SWMA
Catchment disturbance theme	0.73	0.82	0.80
Hydrological disturbance theme	0.96	0.96	0.96

Water quality theme	0.91	1.00	0.96
Physical form theme	0.86	0.82	0.84
Fringing zone theme	0.83	0.77	0.80
Aquatic biota theme	0.79	0.93	0.86
FARWH score (0-1)	**0.83**	**0.86**	**0.85**

10.3.2 Fitzroy River SWMA

Integration of the six themes using Equation 10.19 produced a final FARWH score of **0.78** for the Fitzroy River SWMA (Table 1.5). Lowest scores were recorded for the catchment disturbance (0.71), water quality (0.71) and fringing zone (0.72) themes. Limitations of methods used to derive these scores are discussed in individual theme chapters of this report.

Table 10.53: Integration of the six FARWH themes to a final FARWH score for the Fitzroy River SWMA using Equation 10.19.

Theme	Score (0–1)
Catchment disturbance theme	0.71
Hydrological disturbance theme	0.98
Water quality theme	0.71
Physical form theme	0.85
Fringing zone theme	0.72
Aquatic biota theme	0.90
FARWH score (0–1)	**0.78**

10.4 **Discussion**

Table 10.54 presents results of the desktop and field trials. Results from this field study are also included. However, care should be taken when comparing scores between SWMAs, as methods used were in developmental stages, relied on data from a variety of sources not designed for catchment assessments, and because the spatial coverage of sites assessed in the field trial were limited. Also, aggregation methods may differ within themes (see individual theme chapters in this report and Dixon et al. (2009). An alternative method of integrating theme scores is to simply calculate the mean. The difference in final FARWH scores is minor (0.01–0.02) when compared to the recommended standardised Euclidean distance method. Land and water managers may be more receptive to using a mean score when interpreting the results, rather than the more complex Euclidean method.

Table 10.54: Theme scores for all trial SWMAs used in this report and the desktop trial of FARWH (Dixon et al. 2009).*

Theme	Daly: developed	Daly: undeveloped	Daly River	Fitzroy River	Darwin Harbour	Ord River
Catchment disturbance	0.73	0.82	0.80	0.71	0.87	0.85
Hydrological disturbance	0.96	0.96	0.96	0.98	0.84	0.81
Water quality	0.91	1.00	0.96	0.71	0.89	0.74
Physical form	0.86	0.82	0.84	0.85	0.95	0.73
Fringing zone	0.83	0.77	0.80	0.72	0.84	0.87
Aquatic biota	0.79	0.93	0.90	0.86	0.67	0.85
(a) FARWH (Euclidean Distance)	**0.83**	**0.86**	**0.85**	**0.78**	**0.82**	**0.80**
(b) FARWH (mean)	**0.85**	**0.89**	**0.87**	**0.81**	**0.84**	**0.81**
Difference between (a) and (b)	0.02	0.03	0.02	0.02	0.02	0.01

*** Final FARWH scores are calculated using standardised Euclidean distance (Equation 10.19). An alternative integration method using the mean of theme scores is also included for comparison. Note: methods used for each theme differ between SWMAs.**

11 Testing of indicators to disturbance

11.1 Introduction

The objective of this chapter was to test the response of riparian, water quality and biotic indicators, to a gradient of catchment disturbance.

11.2 Disturbance gradient in the Daly River catchment

11.2.1 Natural landscape variability

Natural variability in broad landscape features among subcatchments of the Daly River was evaluated to account for its influence on the FARWH metrics of river health. Landform categories (Table 11.1) were used to assess dissimilarity among subcatchments. Landform categories were expressed as a proportion of total subcatchment area and analysed using principal component analysis (PCA) (Figure 11.1; Table 11.2)

To compare the landforms in each of the study catchments, a PCA was performed on the proportion of each landform in each catchment (Figure 11.1; Table 11.2). PCAs 1 and 2 accounted for 30.4% and 18.3% of the variation in the original data matrix respectively. The sites located in the upper-left quadrant of the plot are located in sandstone country, with streamflow supplied from Cretaceous sandstone aquifers. These sites were excluded from the fish and macroinvertebrate studies, but retained in the riparian and metabolism studies.

Table 11.1: Landform categories for Daly River catchment disturbance–gradient sites (source NRETAS)

Category	Slopes and soils	Vegetation	% of total area of disturbance-gradient study catchments
LF %3459	Sandstone plateaux, sandy lateritic loams.	Eucalyptus woodland/Acacia sparse shrubland/Triodia tussock grass.	4.9
LF %3461	Gently sloping or undulating lateritic plateaux. Soils, sandy or gravelly, with some sandy loams and loams, extremely low fertility and moisture-holding capacities.	Eucalyptus woodland/Erythrophleum) low, open woodland/Chrysopogon.	3.5
LF %3475	Sandstone, granite and quartzite hills and strike ridges, plains and valleys associated with rocky hills are also common. Shallow or skeletal gravelly sands between sandstone and granite rocks.	Eucalyptus low woodland/Erythrophleum low open woodland/sorghum.	8.3
LF %3482	Slopes and crests of low to steep sandstone hills and plateaux. Well-drained soils, shallow, gravelly sands.	Eucalyptus low woodland/Erythrophleum sparse shrubland/Triodia hum.	3.0
LF %3487	Rugged sandstone plateaux, extensive areas of bare rock. Stony to gravelly shallow sands.	Corymbia low open woodland/Acacia open shrubland/Triodia open hummock grass.	8.5
LF %3509	Poorly drained sites fringing water courses or in drainage depressions. Soils range from yellow podzolics to yellow earths and gravelly sands.	Melaleuca low, open woodland/Pandanus tall sparse shrubland/Chrysopogon.	1.2
LF %3534	Low to steep hills interspersed with sandy plains, shallow gravelly sands, deeper sands on the plains.	Eucalyptus woodland/Eucalyptus tal,l sparse shrubland/Heteropogon.	15.3
LF %3537	Well drained rises and low hills, gently sloping plateaux or plains with well drained sandy and some lateritic red earth soils.	Eucalyptus woodland/Livistona tall sparse shrubland/sorghum.	2.2

LF %3601	Undulating low plateaux and peneplains and rises and upper slopes of ridges. Soils vary from deep, wel- drained, yellow to red earthy sands, varying amounts of lateritic gravels, shallow, sandier soils are common.	Eucalyptus open forest/Livistona low, sparse palmland/Heteropogon.	17.1
LF %3738	Undulating rises and plains, extending onto low hills. Soils, moderately drained loams and sandy loams. Some rock outcrops occur on hillier portions.	Eucalyptus woodland/Erythrophleum low, open woodland/sorghum.	36.1

Figure 11.1:Principal component analysis of landform, based on NVIS database. Vectors are labelled with landform numbers described in Table 11.1. Data was normalised before the analysis.

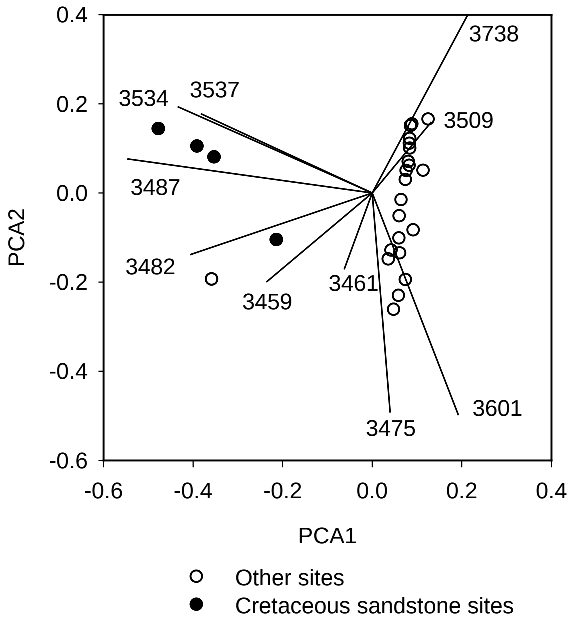


Table 11.2: Eigenvalues for PCA shown in Figure 10.1. Data shown for only the first 3 vectors.

PC	Eigenvalues	%variation	Cum.%variation
1	3.04	30.4	30.4
2	1.83	18.3	48.7
3	1.61	16.1	64.8
Coefficients in the linear combinations of variables making up PC's			
Variable	PC1	PC2	PC3
LF %3459	-0.235	-0.199	-0.574
LF %3461	-0.062	-0.17	0.418
LF %3475	0.04	-0.491	-0.084
LF %3482	-0.405	-0.138	-0.4
LF %3487	-0.545	0.076	0.08
LF %3509	0.131	0.158	-0.013
LF %3534	-0.433	0.193	0.315
LF %3537	-0.381	0.177	0.286
LF %3601	0.192	-0.497	0.348
LF %3738	0.304	0.57	-0.144

11.2.2 Levels of catchment disturbance

The level of catchment disturbance was assessed from a number of databases (listed below and supplied by NRETAS) and from field assessments of cattle impact on the riparian and stream habitats (collected during the field trials).

The landscape-scale data sets were:

1. Euclidean-weighted measure of the distance from grazing land-use to the stream.
2. Euclidean-weighted measure of the distance from intensive land-use to the stream.
3. Euclidean-weighted measure of the distance from land cleared of native vegetation to the stream outlet.
4. Catchment area burnt by fire between August and September in the previous dry season (2008).

In the Daly River catchment, riparian zones and river channels remain largely unfenced, and cattle and feral animals (pigs, buffalo and wild cattle) generally have unrestricted access to these areas. Cattle use the riparian zone for shade, grazing, to drink and to cross to the other bank. Three metrics of cattle disturbance were developed to complement the landscape-scale, GIS-based catchment disturbance indicators. The cattle disturbance metrics provided an on-ground, localised assessment of cattle disturbance. The metrics were:

Cattle track density. Cattle tracks in the riparian zone tend to run parallel to the river bank. These tracks are also used by pigs, buffalo and wallabies. Only tracks that had been used during the dry season were scored. Four categories were identified, and scored 1 to 4 as:

1. No observable cattle tracks (Figure 11.2a).
2. Occasional tracks. Typically a single track along the river bank, not well compacted.
3. Frequent tracks. Typically 1–4 tracks that would divide and reform as a single track, usually compacted.
4. Network of tracks. Many tracks, running parallel to the river bank and joined by intersecting tracks (Figure 11.2b).

Cattle bank access. Tracks in the riparian zone can lead to the river’s lower bank and stream edge (Figure 11.2c, d). The number of currently used tracks leading to the lower bank or stream edge were counted, and expressed as tracks per kilometre. Tracks not being used were not scored.

River edge trampled. Cattle, pigs and buffalo may trample the stream’s edge or enter the stream and trample the riverbed (Figure 11.2e, f). Based on observation, this trampling resulted in the resuspension of sediment and the subsequent smothering of river substrata with fine sediment. The distance of stream edge trampled was estimated for each access point and expressed in metres of trampled edge per kilometre. (Consideration was given to estimating the area of riverbed trampled, but this was considered impractical because it required entry into the river and close observation of the riverbed, which was restricted by light and posed a risk of crocodile attack).

The cattle disturbance metrics were assessed on both banks for a 500 m length of the river. Assessments were made for each 50 m length and then averaged for the cattle track density index or summed for the other two metrics. The field sheet is shown in Figure 11.3. Correlations between each of the three cattle impacts, and with some landscape metrics, were examined (Table 11.3).

Figure 11.2: Images of cattle and feral animal disturbance to the riparian zone, bank and channel edge.

(a) Track density category 4 **(b) Track density category 1 (no evidence).**

(c) Active cattle access to the bank and stream edge (d) past cattle bank and stream (not scored)

(e) Stream edge trampled by cattle **(f) stream edge trampled by pigs.**

Figure 11.13: Field sheet for assessing cattle and feral animal impact to the riparian zone, bank and channel edge

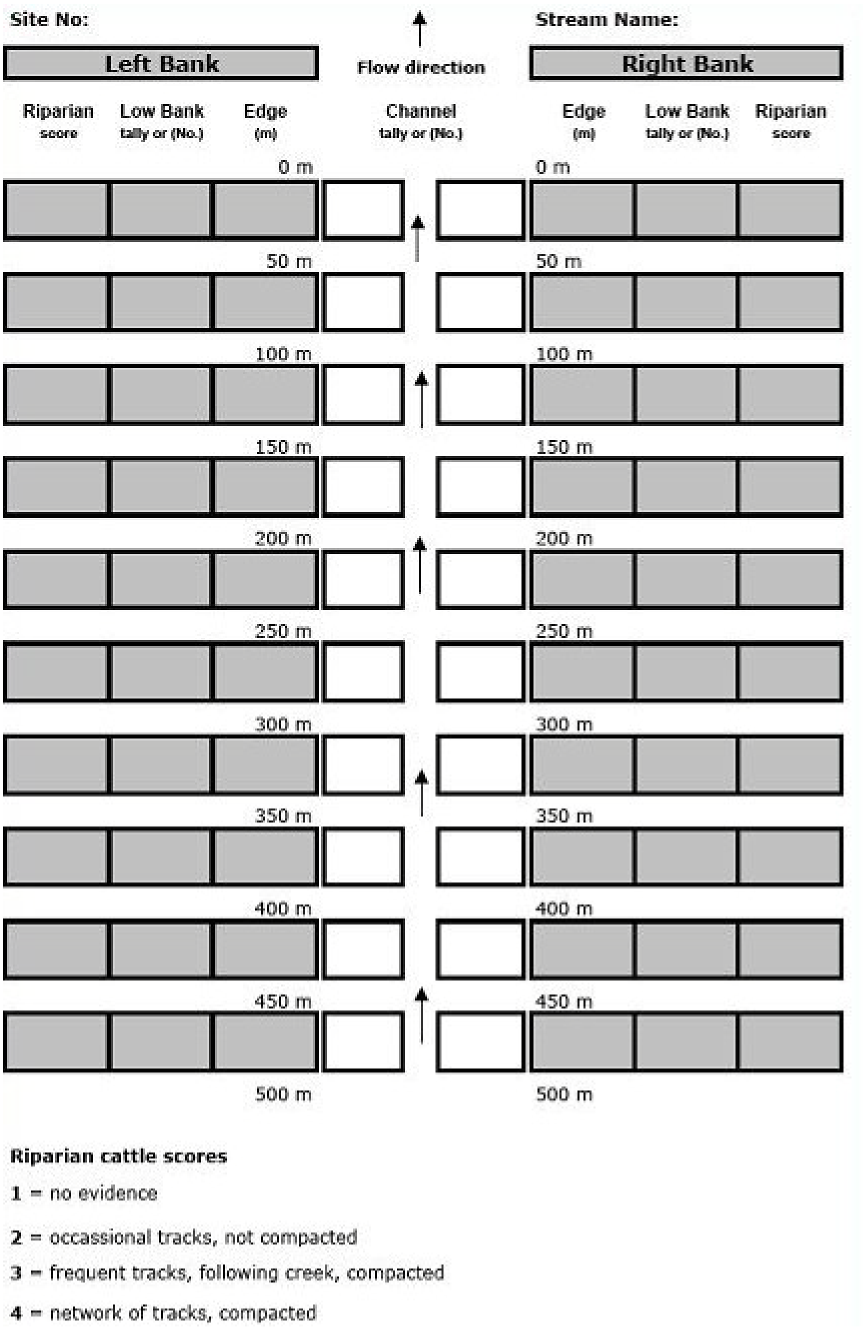


Table 11.3: Correlations between disturbance variables. Cattle metrics in bold.

	%burnt	Grazed land use	Intensive land use	Cleared land	**Track density**	**Bank access**
Grazed land use	0.23					
Intensive land use	0.36	0.54				
Cleared land	-0.08	-0.19	-0.38			
Track density	-0.06	-0.10	-0.43	0.63		
Bank access	-0.04	-0.05	-0.30	0.51	**0.72**	
Trampled edge	-0.10	-0.28	-0.29	0.47	**0.59**	**0.82**

The influence of landscape-scale disturbance (grazing land use, intensive land use, cleared land and area burnt and the cattle disturbance metrics was investigated using a PCA. The PCA demonstrates a gradient of disturbance exists between sites (Figure 11.4 and Table 11.4), and that the land area cleared and cattle impacts account for the greatest spread of sites on the ordination plot (Table 11.3). Principal components (PC) 1 and 2 accounted for 46% and 21% of variation respectively. PC 1 was best correlated (r≈ -0.45) with the 'cleared native vegetation' and the three cattle disturbance metrics (track density, bank access and trampled edge), while the landscape variables were best correlated with PC 2 (r≈ -0.5.)

Figure 11.4: Principal component analysis of disturbance metrics. Data was normalised before the analysis.

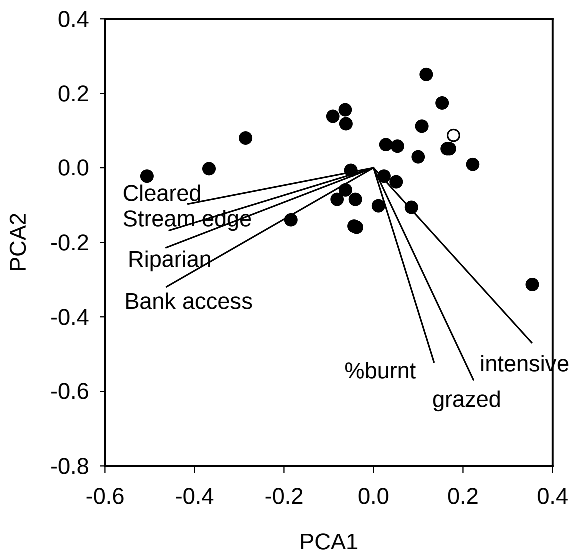


Table 11.4: Eigenvalues for PCA shown in Figure 11.4. Data shown for only the first 3 vectors.

PC	Eigenvalues	%variation	Cum.%variation
1	3.25	46.4	46.4
2	1.48	21.2	67.5
3	0.79	11.3	78.8
Coefficients in the linear combinations of variables making up PCs			
Variable	PC1	PC2	PC3
% burnt	0.135	-0.521	0.806
Grazed land use	0.223	-0.569	-0.553
Intensive land use	0.353	-0.469	-0.122
Cleared	-0.414	-0.097	0.081
Track density	-0.463	-0.214	-0.069
Bank access	-0.462	-0.319	-0.133
Edge trampled	-0.456	-0.168	0.006

11.3 Daly catchment TRARC response to the disturbance gradient

TRARC was applied in the FARWH trials to assess riparian condition for the fringing zone theme (see Chapter 8). The relationship between TRARC and cattle disturbance was examined through simple scatter plots of the track density and cattle bank-access metrics against the TRARC indices. Track density and bank access were correlated (Figure 11.5a), while the TRARC overall pressure index was related to TRARC overall condition (Figure 11.5b). Additionally, the TRARC animal index was related to the track density and bank access scores (Figure 11.5c, d) The animal-damage subindex, and its component managed-animal index, were related to the TRARC condition (Figure 11.5e, d), which, in turn, was related to the track density and bank access scores. Overall, the relationships between the TRARC indices with cattle disturbance were internally consistent and supported by the two measures of cattle disturbance that were independent of the TRARC assessment. Regression coefficients were between 0.2 and 0.4.

The TRARC condition index represents the aggregation of five subindices. Figure 11.6 shows the relationships between each TRARC subindex score and the track density and cattle access metrics. The plant regeneration and weeds subindices were statistically significant (r^2=0.11–0.20), while plant cover, erosion and bank stability were not. After Bonferroni correction, however, no tests were significant. When compared with the TRARC animal-damage subindex, the plant-cover and erosion subindices were not significant. However, the plant regeneration (r^2=0.21; p=0.013), weeds (r^2=0.37; p<0.001; weeds increase with animal damage), and bank stability (r^2=0.16; p=0.032) were significant (not shown in figure). The significant though low regressions between the animal damage and bank stability index contrasts with the nonsignificant results for track density and cattle-access analyses. At the TRARC subindex level, there was, at best, a trend of reduced plant regeneration, increased weeds and possibly lower bank stability with increased cattle disturbance. These weak relationships may represent an artefact of the aggregation process or, indeed, that the disturbance is relatively minor, but are not supported by strong statistical evidence, either in terms of high regression coefficients or significance levels after Bonferroni corrections.

Relationships between each indicator of the TRARC subindices (plant cover, regeneration, weeds, erosion, bank stability) and cattle disturbance were examined. A single disturbance metric (cattle-track density) was used to minimise the overall error rate of the tests, with the results shown in Table 11.5. Twenty-eight tests were conducted, and the level of significance adjusted by the Bonferroni method. Two tests (regeneration of nondominant trees; understorey of weeds) were significant and four tests were almost significant (regeneration canopy health, weeds litter, bank maximum sediment size, in-stream structures).

The data that underlies TRARC are category scores between 1 and 5 based on field observations. Consequently, information, such as the range of indicator values, are reinterpreted and the true range generally down-weighted. For example, tree size is classed as 1 (no canopy or uniform tree sizes), 3 (two distinct size groups) and 5 (3 + distinct size groups). Canopy-cover weights the near-absence of canopy cover with a score of 1 (<5%), compared to the other canopy scores: 2 (5–25%), 3 (25–50%), 4 (50–75%) and 5 (75–100%). A relationship may exist at the indicator level, but due to categorisation, substantial information can be lost in the classification approach.

To address this, we sought relationships between the raw data and the two cattle disturbance measures. This was often constrained by an ‘open’ upper category. For example, dominant tree regeneration had three categories: 0, 1–3, and 4+. Eighteen of the indicators were expressed as percentage ranges. This took two forms; almost equal weighting for the categories as shown for canopy cover, or a more marked weighting such as ‘mid-storey canopy cover’, which was categorised as 1 (<5%), 2 (5–30%) and 3 (>30%). The TRARC weighting seeks to emphasise the effect of disturbance on a riparian attribute.

To examine whether raw data was related to cattle disturbance, two indicator raw values were plotted against disturbances measures (Figure 11.7). Use of the raw data comprised the middle value of a category range. A significant relationship was found for mid-storey native vegetation cover for track density and bank access, though not for understorey native vegetation cover.

While at the highest level of TRARC condition, a relationship existed between disturbance and riparian condition, but this was less evident at the subindices and indicator levels. The significant high-level relationship may have been an artefact of the aggregation process. Overall, especially when examined at the indicator level, the impact of cattle on riparian condition was minor or not detected by TRARC. The use of categories in TRARC may reduce the sensitivity of its subindices. Assuming cattle impacts are minor, it may be more appropriate to direct effort at the collection of more detailed information on the most vulnerable component of the riparian environment, rather than assessment of the many TRARC indicators. A confounding issue is that the TRARC site values are not compared to a reference condition, and so the scores between sites may not be comparable if their reference condition differed. TRARC may not be suitable for landscape-scale assessments of riparian condition, but may be suitable instead for site specific assessments.

Figure 11.5: Relationships between independent variables animal track density and bank access, and TRARC indices for 250 m distance. Statistics shown for statistically significant regressions (with no account for an overall error rate of multiple tests).

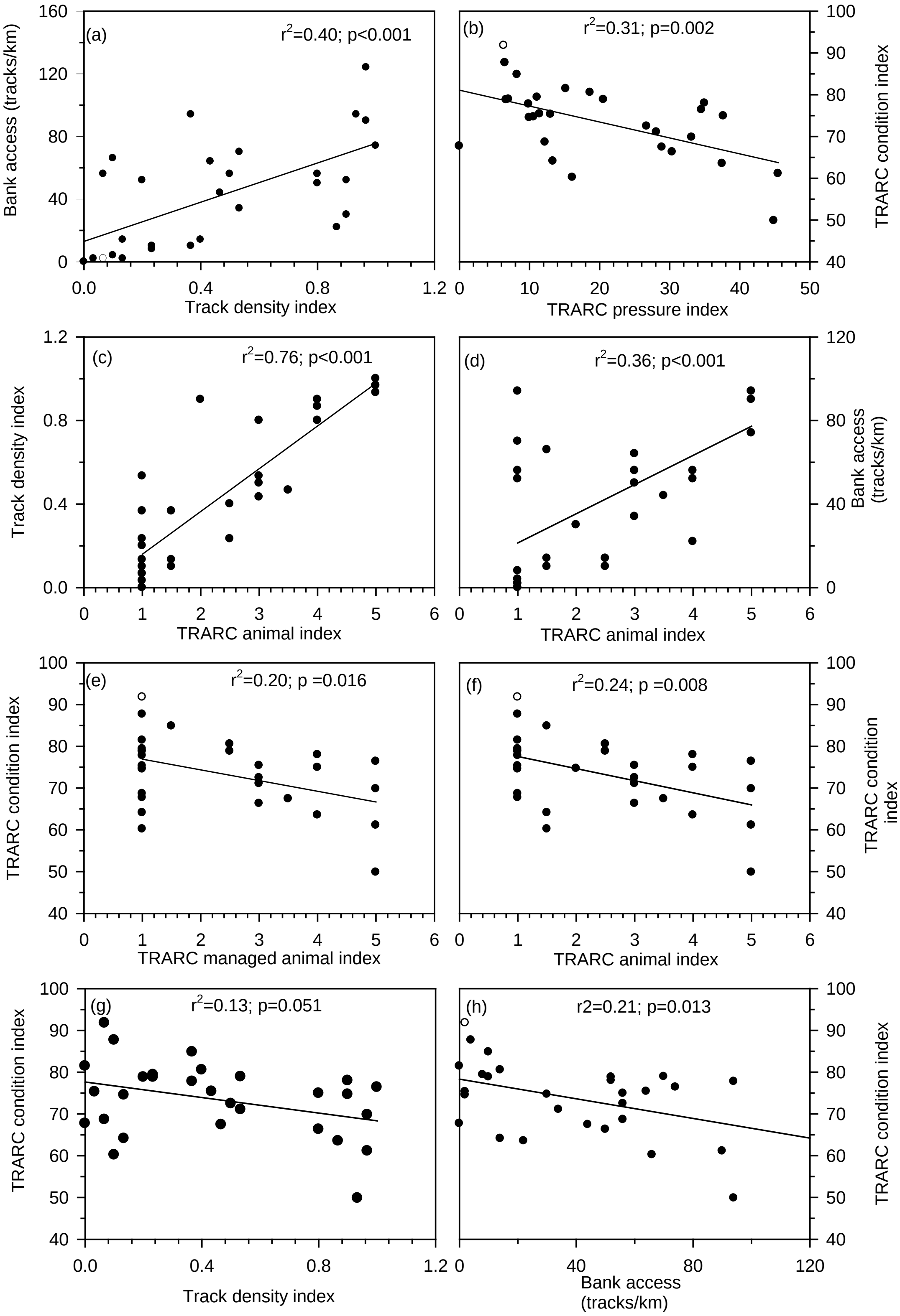


Figure 11.6: Relationships between cattle disturbance (250 m assessment) and TRARC subindices. No tests are significant when significance is adjusted by the Bonferroni method (level of significance = 0.005).

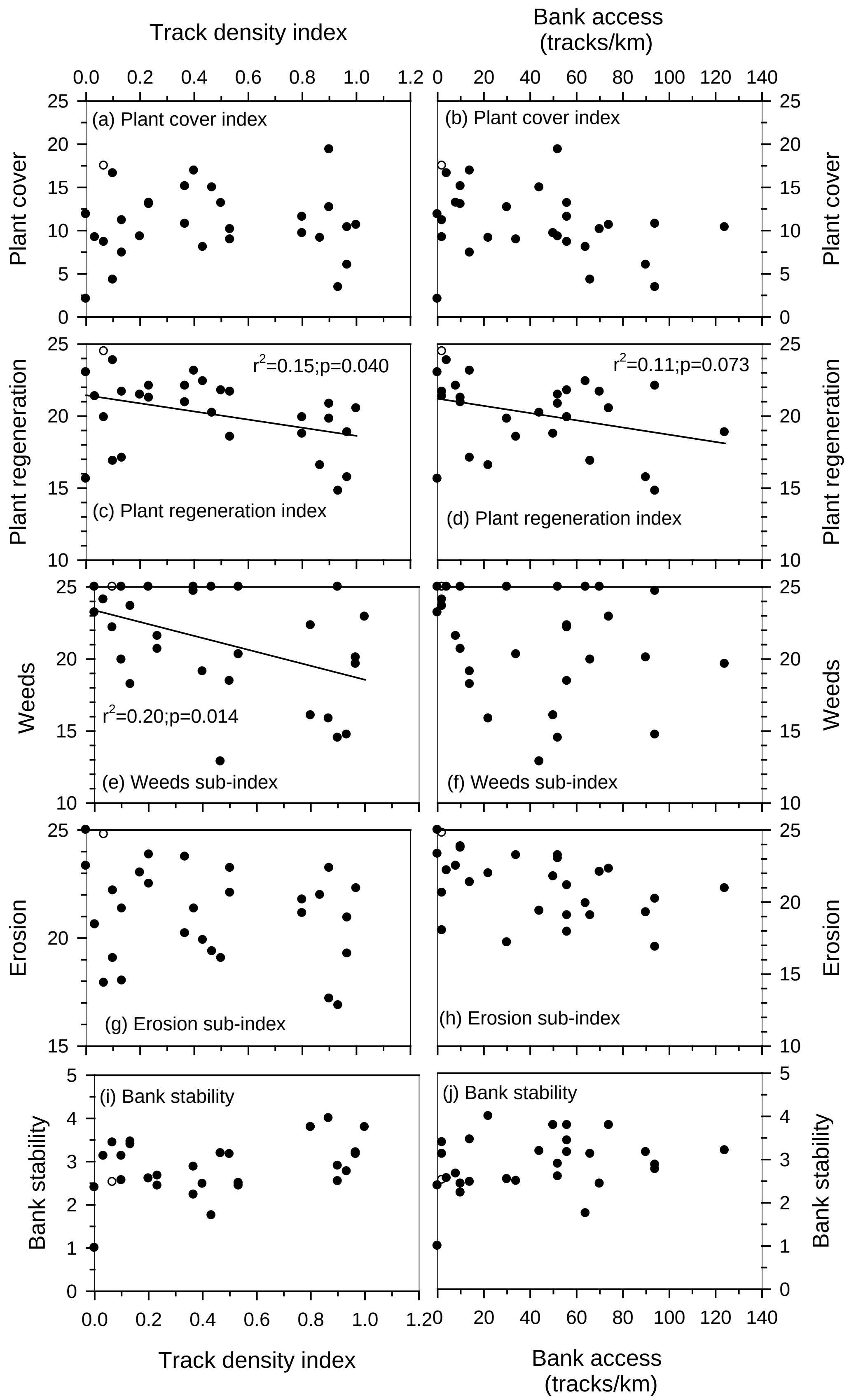


Table 11.5: Linear regression coefficients between TRARC subindex indicators and track density index and, in parentheses, significance levels where regressions exceed 0.1.* Bonferroni-corrected level of significance (28 tests, initial level 5%) is 0.0018, and are highlighted when close to this level.

(a) TRARC regeneration subindex (5 tests)

Regeneration subindex	Canopy health	Large trees	Tree size	Dominant trees	Other trees
Track density index	**0.29 (0.003)**	0.02	0.02	<0.01	**0.43 (<0.001)**

(b) TRARC plant cover subindex (7 tests)

Plant Cover subindex	Canopy cover	Canopy continuity	Mid-storey cover	Under-storey cover	Grass cover	Organic litter	Logs
Track density index	<0.01	0.02	0.21 (0.012)	0.01	<0.01	0.01	0.17 (0.023)

(c) TRARC weed subindex (7 tests)

Weeds subindex	Weed canopy	Mid-storey weeds	Under-storey weeds	Grass weeds	Litter weeds	High impact weeds	High impact distribution weeds
Track density index	<0.01	<0.01	**0.26 (0.005)**	0.16 (0.033)	**0.27 (0.004)**	0.08	0.22 (0.010)

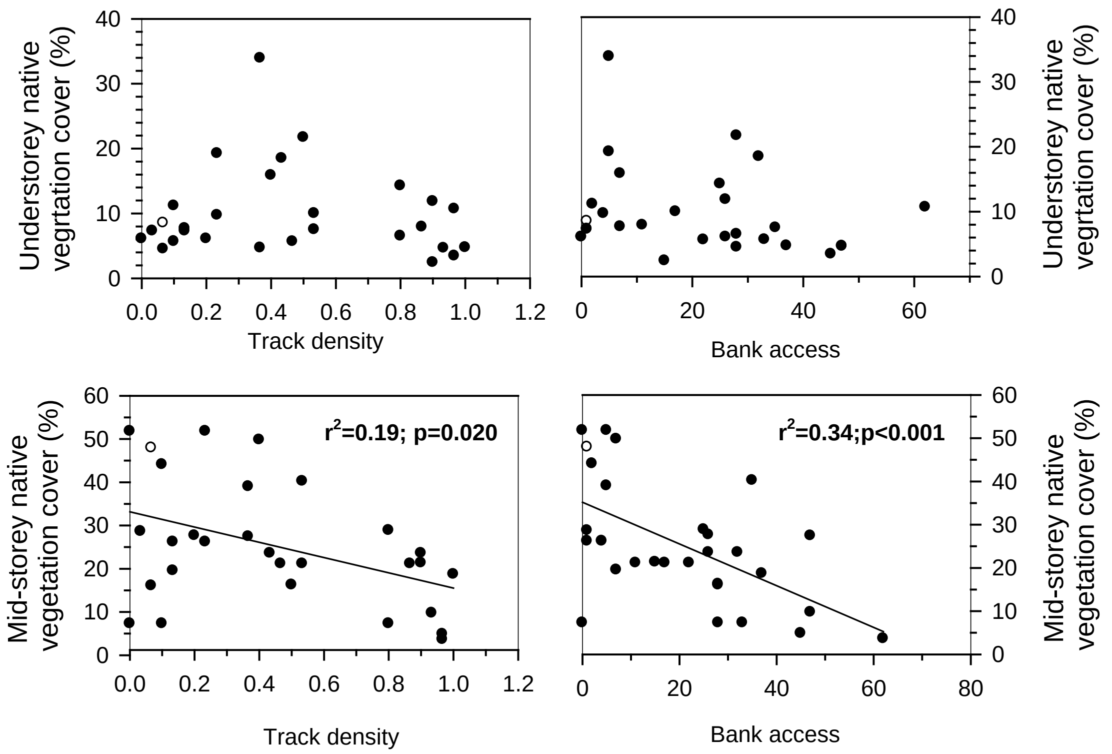
(d) TRARC erosion subindex (5 tests)

Erosion subindex	Exposed soil	Exposed tree roots	Slumping	Gullying	Under-cutting
Track density index	0.11 (0.076)	0.11 (0.076)	<0.01	<0.01	<0.01

(e) TRARC bank stability subindex (4 tests)

Bank stability subindex	Maximum sediment size	Dominant sediment size	Bank slope	Instream structures
Track density index	**0.34 (<0.001)**	0.16 (0.03)	0.08	**0.28 (0.003)**

Figure 11.7: Relationships between TRARC raw data and disturbance metrics (250 m data equivalent to the TRARC survey distance).



11.4 **Metabolism**

The concentration of dissolved oxygen (DO) in rivers is a function of oxygen exchange at the river's surface, oxygen production by photosynthesis, and oxygen consumption by respiration (Odum 1956). When photosynthesis is the only source of carbon fixation, which is typically the case as anaerobic carbon fixation is considered negligible, photosynthesis equals gross primary production. Respiration is undertaken by autotrophs and is linked to photosynthesis, and by heterotrophs utilising both autochthonous and allochthonous sources of carbon. Rates of photosynthesis and respiration are collectively referred to as river metabolism, and identified as one of five fundamental ecosystem processes (Giller et al. 2004). Because metabolism is primarily a function of a river's aquatic biota (bacteria, fungi and aquatic flora and fauna), it is considered under the aquatic biota theme, rather than the water quality theme where the DO indicator is assessed as a stressor to fish.

Metabolism is responsive to many stressors, including, nutrient, chemical and sediment pollution, flow alteration, the condition of the riparian vegetation, channellisation, and aquatic plant management (Young et al. 2008). It may be determined by either the use of chambers, which provides substrate specific rates, or by the open-channel method, which integrates measurements of DO over a river reach. This FARWH project considered only the single-station, open-channel method. Mulholland et al. (2005) have shown that river metabolism can be correlated to catchment disturbance, the diurnal amplitude in DO correlated to primary production, and maximum deviation from oxygen saturation correlated to respiration.

It is likely metabolism may be more responsive to anthropogenic impacts in warm waters of the wet/dry tropics because of their lower oxygen content and higher oxygen demand relative to colder temperate waters. DO concentrations in warm waters are more vulnerable to hypoxia than colder waters due to the lower solubility of oxygen: the saturated DO concentration of water at 32 °C—a typical end-of-dry season river temperature—is 7.3 mg/l, while at 10°C the saturated DO concentration is 50% higher. Additionally, warm waters are more vulnerable to hypoxia, not only due to the lower oxygen concentrations, but also the faster rates of microbial respiration, which approximately doubles for every 10 °C.

In this section, we explore the potential use of river metabolism, measured by the open channel method, using two indicators developed by Mulholland et al. (2005). These are the amplitude of the diurnal DO and the maximum DO deficit from 100% saturation levels. These metrics make use of two points (or more if a running average is used) on the diurnal curve: maximum and minimum DO. (In contrast, the calculation of photosynthesis and respiration makes use of the whole diurnal curve).

We examined 1) the relationship between photosynthesis and respiration, and metabolism metrics; 2) the diurnal patterns of DO; and 3) the relationship between catchment disturbance and metabolism metrics. We also briefly discuss the establishment of suitable reference conditions and scoring methods for inclusion of this metric into future FARWH assessments.

11.4.1 Relationship between metabolism and dissolved oxygen metrics.

The relationship between metabolism and DO was investigated, using estimates of dry season metabolism made at four reference sites in the Daly River catchment. The data has been reported by Schult et al. (2008) and applied the method of Webster et al. (2005) for the calculation of photosynthesis (P) and respiration (R). The assumptions that underlie this method are that primary producers and the flow and morphology of the river reach are uniform, and that groundwater does not enter the study reach.

The relationship between P and the DO amplitude, and R and the DO deficit, is shown in Figures 11.8 and 11.9, with DO expressed as both a concentration and percentage saturation. Amplitude has coefficients of determination with P of 0.68 for concentration and 0.86 for percentage saturation. DO deficit expressed as a concentration has site-specific relationships with R, rather than a regional one (r^2 <0.01). However, when the deficit is expressed as percentage saturation, the coefficient of determination is 0.67. We conclude that the amplitude and deficit metrics can provide a reasonable surrogate for river metabolism when expressed as percentage saturation.

11.4.2 Diurnal patterns of dissolved oxygen.

Diurnal DO curves typically reach their maxima at solar noon and minima at sunrise. The DO curve approximates a sinusoidal curve during the daylight hours, and during the night is linear until depletion . This assumes the rate of photosynthesis does not reach levels where photo-inhibition occurs, thus decoupling light intensity and photosynthesis.

Most diurnal curves approximated the ideal; an example is shown in Figure 11.10a. About 20% of curves, however, deviated substantially from this model and showed an increase in DO concentrations during the night; for example, the rise after 1 am at site DG02 shown in Figure 11.10b. The most likely explanation for such an atypical curve is that the assumption of homogeneity required for the single station method has not been met, and that upstream primary production and stream morphology vary and produce parcels of water with different dissolved oxygen histories.

The implications for the metabolism metrics are not clear and are dependent on the extent of the deviation from that expected. The DG02 curve would be expected to continue to decline after 1 pm to reach a lower minimum than actually occurred. Thus, the amplitude and deficit would be underestimated if ideal conditions existed. Instead, the actual amplitude and deficit are also a function of the river’s heterogeneity and not just river metabolism. The significance of this is not clear, and may be minor if there is a wide range of P and R values.

11.4.3 Relationship between catchment disturbance and metabolism metrics

The premise underlying the use of metabolism is that it will be responsive to the disturbance by cattle and feral animals (pigs and buffalo). Higher rates of photosynthesis, and hence increased DO diurnal amplitude, may be expected if nutrients are introduced to streams from animal wastes (though this may also be mitigated by higher siltation, which could smother benthic algae). Higher rates of respiration could also be expected, and a greater DO deficit, if organic material is introduced to the stream or resuspended from the streambed.

To examine the relationships between DO amplitude and maximum deficit, scatter plots were produced and regressions computed between these metrics and the most relevant environmental variables. Amplitude was plotted against nutrients (total nitrogen (TN) and phosphorus (TP), oxidised nitrogen (NOx), filterable reactive phosphorous (FRP), River Disturbance Index (RDI; Stein et al. 2002) and canopy cover. These plots showed no statistically significant linear relationship between nutrient concentrations (Figure 11.11), RDI or canopy cover (latter not shown). Soluble and total nutrients were both generally low, and could be defined as oligotrophic or mesotrophic. Canopy cover averaged 74%, and was greater than 52% except for one site which had a cover of 1%.

The absence of a relationship between amplitude and nutrients is probably due to low nutrient concentrations (see Chapter 6), which is indicative of an absence of significant eutrophication, which the DO diurnal amplitude is sensitive to. The disturbance gradient, it seems, did not include nutrient enrichment and eutrophication, and consequently was not suitable for testing the DO amplitude metric.

Maximum DO deficit was plotted against stream-edge disturbance (Figure 11.12), which is an indicator of animal, mainly cattle, trampling the stream water's edge and streambed. The deficit tended to increase with the percentage of stream edge disturbed. When an outlier is removed, regressions between deficit as both a concentration and percentage saturation have coefficients of determination of almost 0.3. A significant regression is also obtained for the RDI and maximum deficit measured as a percentage of saturation, but not when the deficit is expressed as a concentration. The significant regressions are weighted by a single high disturbance-deficit data point which, if removed, results in nonsignificant regressions, though there is no reason for this to be done.

Cattle are unlikely to be the only factor that contributes to the variation in the maximum oxygen deficit in rivers. Another factor is the bathymetry of the upstream reach, and the occurrence of pools and stream depth. Pools could affect DO concentrations by exerting a high-sediment oxygen demand which, when combined with reduced velocities (and increased retention times), consume oxygen at a faster rate than in riffles and runs. Depth could affect the deficit as an index of stream volume. The scatter plots in Figure 11.13 reveal a high DO deficit is more likely when the %pool increases. While the %pool regressions are significant, the data did not conform to a normal distribution, and could not be transformed because of the relatively high number of pool percentage values close to both 0% and 100%. Spearman rank correlations were significant between %pool and the maximum DO deficit expressed as either a concentration ($r=0.66$; $p<0.001$) or percentage saturation ($r=0.68$; $p<0.001$). No relationship was evident between DO deficit and average river depth, similar to Mulholland (2005).

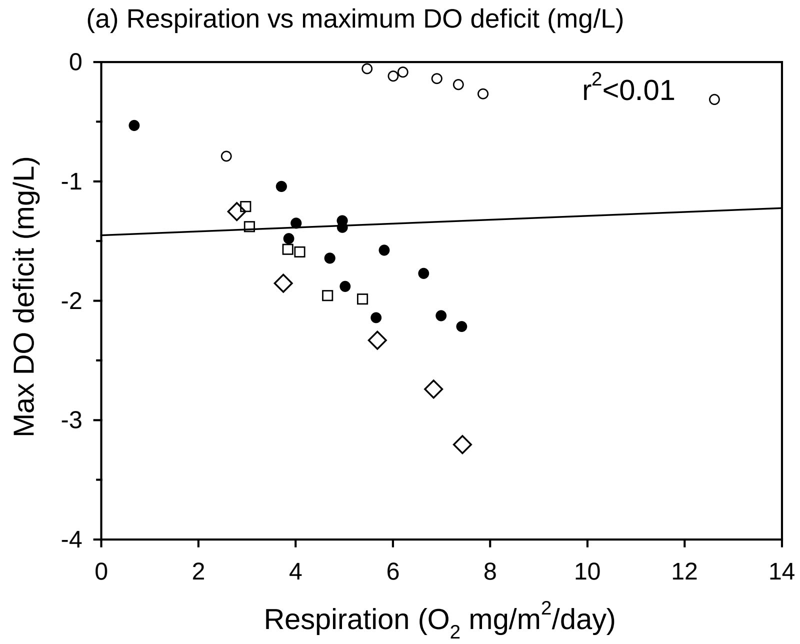
Evidence for a decrease in the maximum DO deficit caused by cattle access to streams is weak, though there is evidence that the size of upstream pools has an influence. The analysis presented here proved to be constrained by the lack of normality in the cattle disturbance data, even after data transformation. Maximum DO deficit, if found to be useful, would need to be standardised for the percentage of pool upstream.

11.4.4 Reference condition and assessment of disturbance on river metabolism.

If sites monitored in 2005 are considered in reference condition, then the 95% percentiles approximate 4.0 mg/l and 40% saturation for the DO amplitude, and 3.2 mg/l and 45% for the maximum DO deficit. In 2009, a single site exceeded this threshold for the amplitude metric, while five sites exceed the deficit expressed as a concentration and three sites when it is expressed as a saturation level. To score these metrics between 0 and 1 requires more research into better understanding the impact of all disturbances on metabolism.

We conclude that the use of river metabolism needs to be further examined as an ecological indicator before its adoption in FARWH. Development of this indicator could provide additional value to diurnal dissolved oxygen data measured for water quality assessment.

Figure 11.8: Relationships between photosynthesis and a) diurnal dissolved oxygen amplitude expressed as a concentration, and b) expressed as percentage saturation. Data from Schult et al. (2007) for 4 sites monitored over the dry season in the Douglas–Daly region.



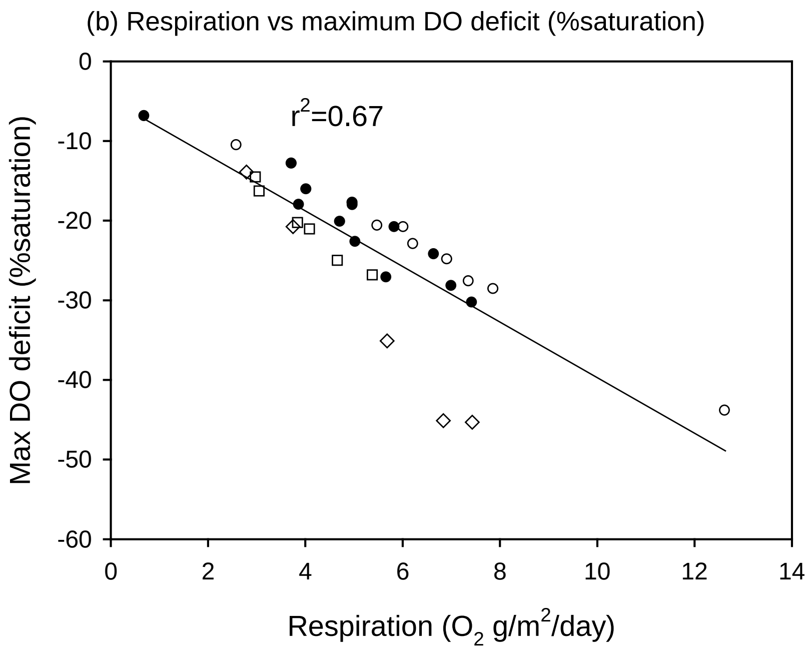


Figure 11.9: Relationships between respiration and a) maximum dissolved oxygen deficit expressed as a concentration, and b) expressed as percentage saturation. Data from Schult et al. (2007) for 4 sites monitored over the dry season in the Douglas–Daly region.

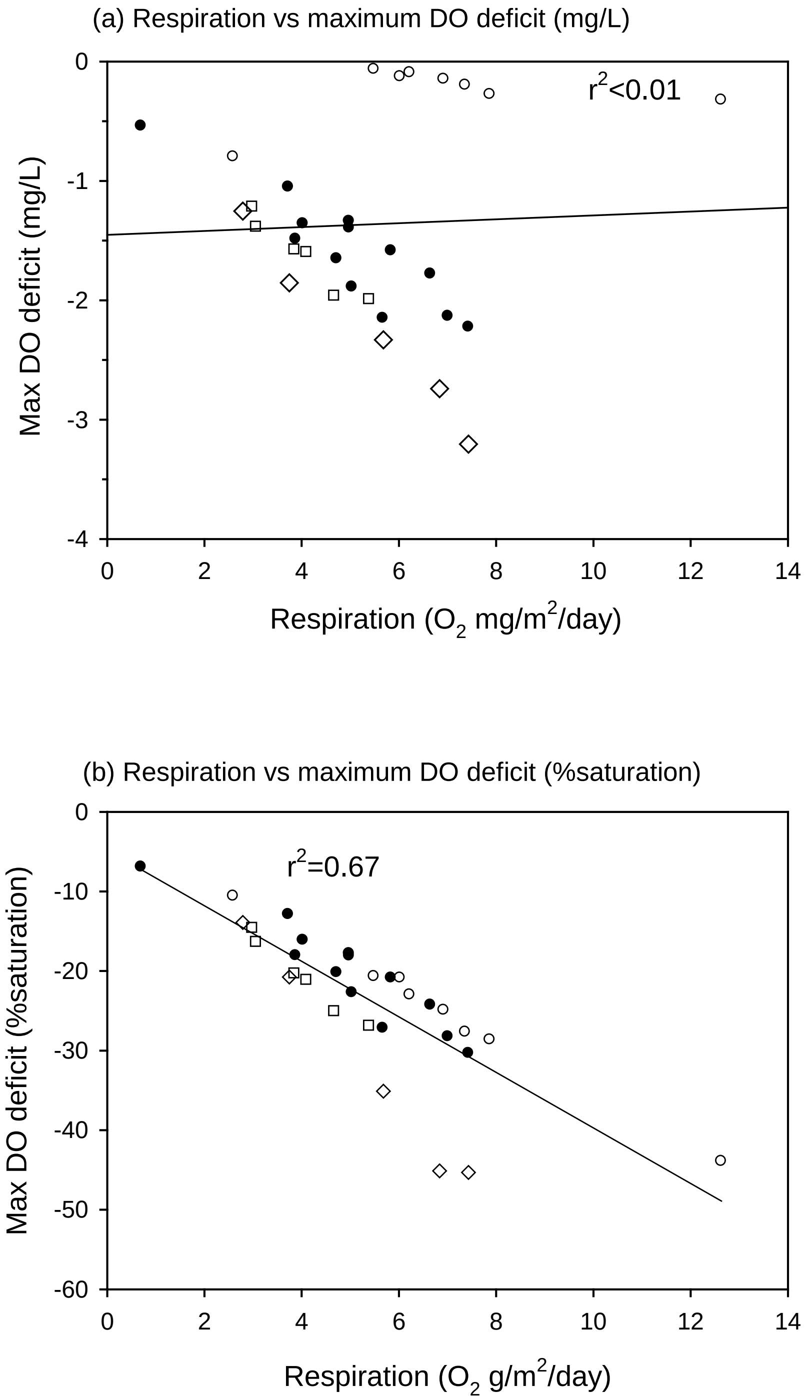


Figure 11.10: Diurnal dissolved oxygen for a) curve that conforms with diurnal theoretical model, and b) curve showing increase in dissolved oxygen at 1 pm, and does not conform with model curve.

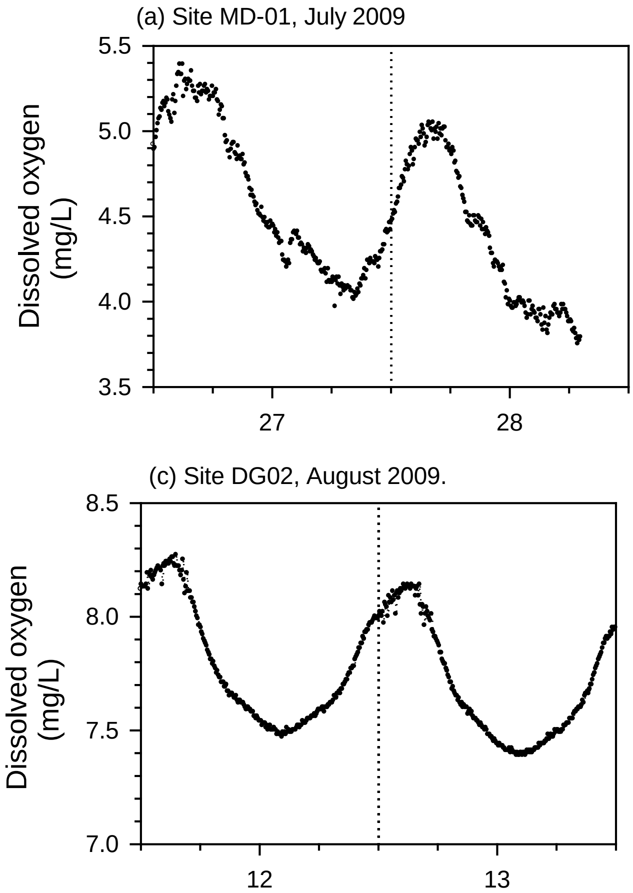


Figure 11.11: Relationships between dissolved oxygen diurnal amplitude and a) filterable reactive phosphorus, b) total phosphorus, c) oxidised nitrogen and d) total nitrogen for the 2009 disturbance gradient data set.

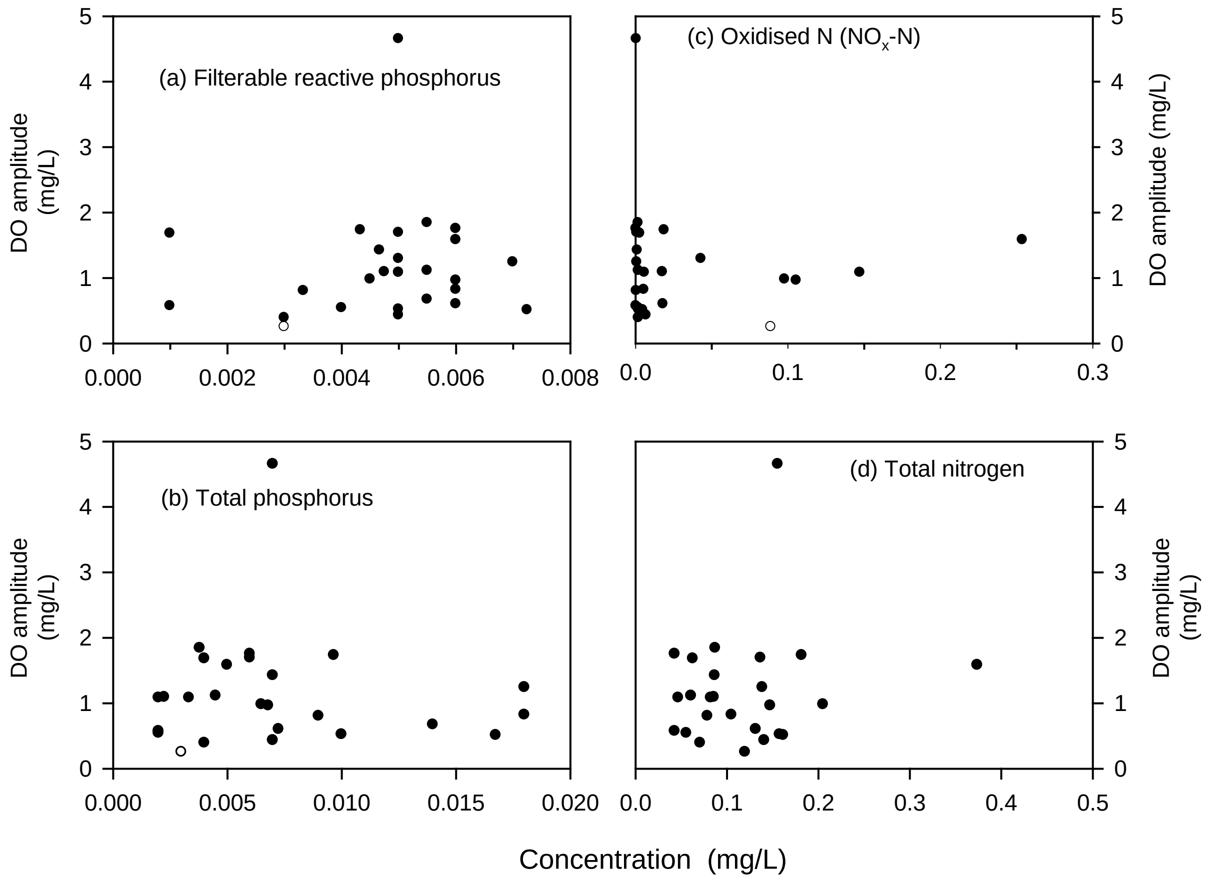


Figure 11.12: Relationships between disturbance determined as a, b) trampled stream edge and c, d) the river disturbance index, and maximum diurnal deficit expressed as a concentration, and percentage saturation.

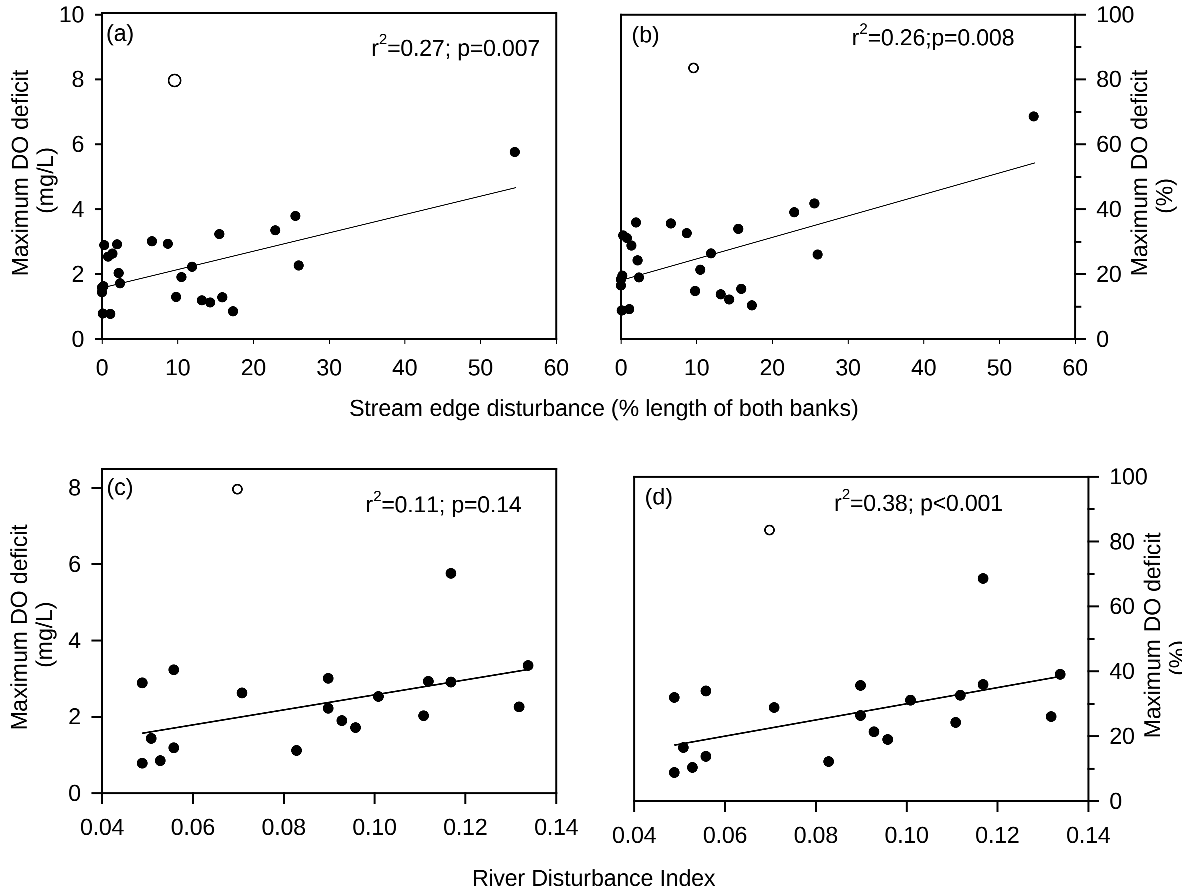
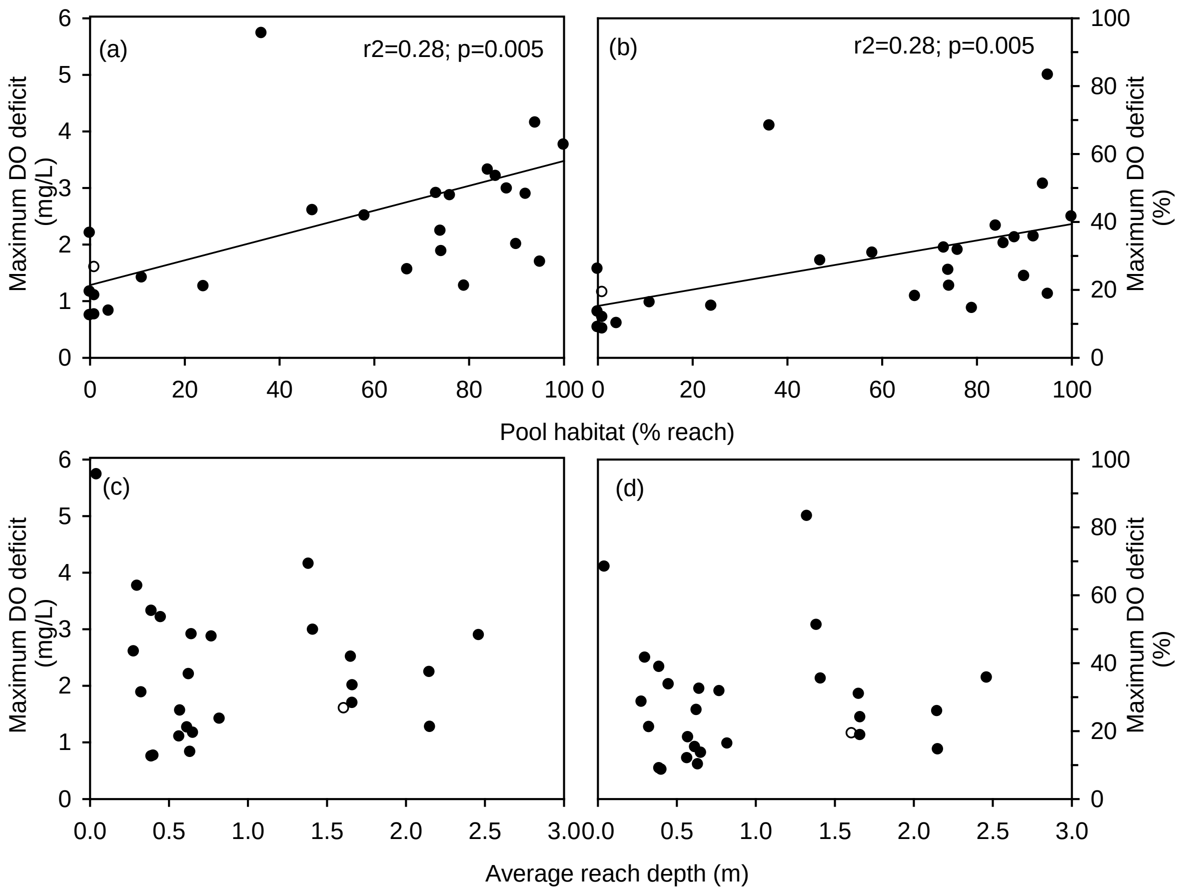


Figure 11.13: Relationships between maximum DO deficits and stream habitat and average depth.



11.5 **Literature cited**

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11.6 Aquatic biota

11.6.1 Introduction

Biological assessments depend on knowledge of the response of biological indicators to disturbance. We sought to examine the response of fish and macroinvertebrate communities to varying levels of landscape disturbance due to grazing. Fish and macroinvertebrate communities were sampled using standardised methods; several metrics of landscape disturbance were derived at site and catchment scales. The following analyses examine between site variation in environmental attributes, correlates of variation in community composition, and model relationships between environmental variables including disturbance related variables and biological metrics.

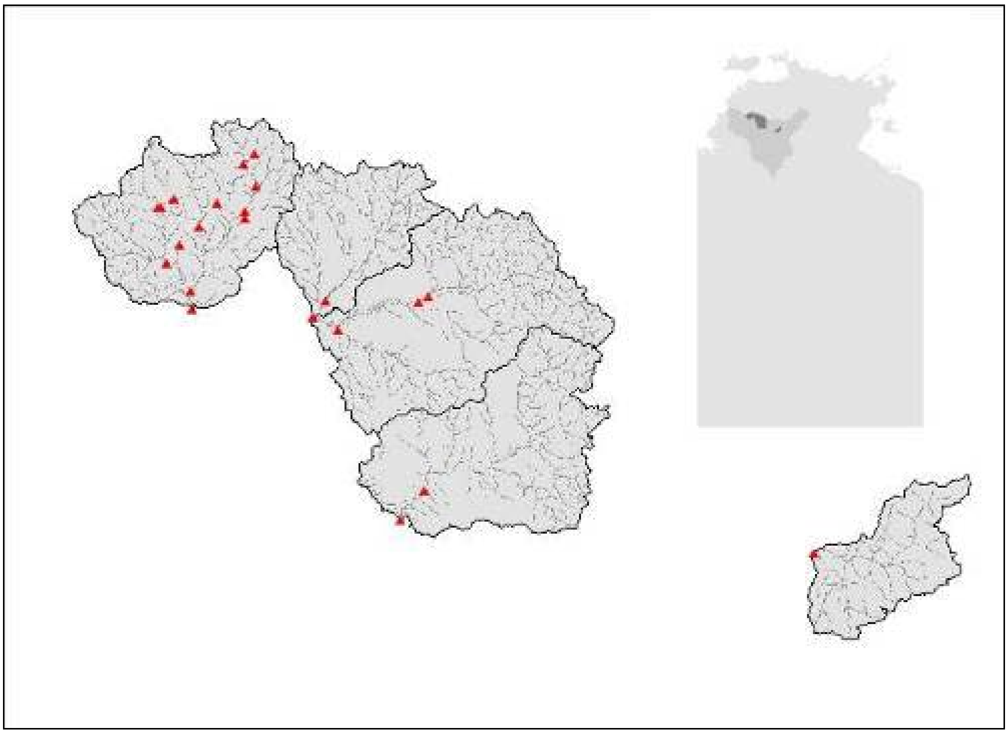
11.6.2 Methods

These analyses were limited to 23 sites at which data was collected for assemblages of fish, macroinvertebrates and chironomid pupal exuviae. The distribution of survey sites is shown in Figure 11.14. Sample-site catchments ranged between approximately 2 and 1200 km^{2,} with stream orders of 1–4 based on 1:250 000 stream mapping. Sites are concentrated in the northern portion of the Daly River catchment. Fourteen of the 23 sites were located in the catchment of Green Ant Creek on Tipperary Station. Most of these sites have relatively small catchment areas (mean catchment size 157 km^2 versus overall mean catchment size of 330 km^2). Sampling was conducted between June–October 2009.

Biotic data

Fish were sampled using standardised electrofishing methods, using a backpack electrofisher in wadeable sections of streams. Macroinvertebrate samples were collected using methods prescribed for the NT AUSRIVAS edge-habitat model. Samples were preserved in 70% ethanol and sorted in the laboratory using a Wild stereomicroscope. Chironomid larvae were mounted in Hoyer’s fluid and examined at high magnification using an Olympus Vannox microscope. Most specimens were identified to genus level, using regional taxonomic keys. Chironomid pupal exuviae were sampled by collecting surface flotsam at several points at the site using a 250 µm sieve. Samples were preserved in 70% ethanol and sorted in the laboratory. All exuviae were mounted on microscope slides with Hoyer’s fluid and examined at high magnification with an Olympus Vannox microscope. All specimens were identified to species type using regional taxonomic keys.

Figure 11.14: Distribution of 23 survey sites sampled for fish, macroinvertebrates and chironomid pupal skins. Inset shows location of survey catchments in Daly River catchment in the Northern Territory.



Environmental data

Eleven environmental variables were used in statistical analyses (Table 11.16). These included three variables describing landscape position (stream order, distance from source and catchment area), three variables describing landscape disturbance (bank cattle index, catchment clearing and catchment land use) and five variables related to water quality (pH, electrical conductivity, turbidity, total nitrogen and total phosphorus). The bank-cattle index was the count of the number of cattle tracks traversing the bank measured on 500 m transects on both stream banks, and expressed as number per kilometre; catchment clearing is the ratio of the sum of inverse-weighted distances from the sample site within cleared and uncleared strata. This was calculated using raster maps of the catchment and clearing data within ArcGIS. Clearing data was the NRETAS 2008 land-clearing data. Catchment land use was the HDI derived from the proportions by area of land-use classes as described in Chapter 4. An additional variable (reach disturbance index RDI) was used as a predictor variable in generalised linear modelling. RDI for each site was derived from data compiled Stein et al. (2002).

Table 11.16: Extrinsic environmental variables used in analyses of disturbance gradient.

Environmental variables	Description
Landscape position	
Stream order	Strahler method using 1:250 000 mapping.
Distance from source	Calculated using digital mapping at 1:250 000.
Catchment area	Estimated using catchment delineation methods in ArcGIS.
Landscape disturbance	
Bank cattle index	Number of cattle tracks to water per km.
Catchment clearing	Inverse-weighted distance from site (EucO).
Catchment land use	Catchment land use coded by ALUM classes.
Stream water quality	
pH	
Electrical conductivity	
Turbidity	
Total nitrogen	
Total phosphorus	

Statistical analyses

Three statistical methods were used to analyse the data. Firstly, PCA was used to examine similarities between sites, based on environmental variables. PCA was conducted using the R software package (R Development Core Team 2008). All variables were normalised prior to analysis. Principal components derived from this analysis are used as an integrated measure of disturbance in subsequent generalised linear modelling. Secondly, the structure of faunal assemblages (fish, macroinvertebrate and chironomid pupal exuviae) in relation to extrinsic variables was examined using procedures using the PRIMER software program version 6 (Clarke and Gorley 2006). Multidimensional scaling (MDS) ordinations were conducted using presence/absence data and the Bray Curtis dissimilarity measure. The procedures BIOENV and RELATE were used to explore the relationships between assemblage structure and extrinsic variables, and between multivariate datasets. Generalised linear modelling was conducted using the R software package. The Akaike Information Criterion corrected for small sample size (AIC_c) (Burnham and Anderson 2002) was used as an objective means of model selection. The approach identifies the most parsimonious model from a set of candidate models given maximised log-likelihood of the fitted model. The relative values (AIC_c differences or d.AIC_c) of each model over the set of models being considered were taken as the relative level of empirical support for each model. Values between 0–2 provide substantial support, 4–7 considerably less and >10 essentially none (Burnham and Anderson 2002). Given AIC_c differences for each model, the relative likelihood of a set of candidate models was calculated using Akaike weights (wi). The weight of any particular model depends on the entire set of candidate models, and varies from 0 (no support) to 1 (complete support). The number of model parameters is given by k.

For each of four biotic indicators (fish O/E, fish species richness, macroinvertebrate O/E, chironomid pupal richness), two sets of candidate models were considered (Table 11.7).

Table 11.7: Candidate models for two sets of variables used in analysis of disturbance gradient.

Set 1		Set 2	
Model 1	Null	Model 1	Null
Model2	PC1	Model 2	Clear
Model3	PC2	Model 3	Reach disturbance index (RDI)
Model 4	PC1 + PC2	Model 4	Catch
Model 5	PC1*PC2	Model 5	Bank cattle index (BCI)
		Model 6	Catch + RDI
		Model 7	Catch + Clear
		Model 8	Catch + BCI
		Model 9	Catch*RDI
		Model 10	Catch*Clear
		Model 11	Catch*BCI
		Model 12	Clear + RDI + Catch + BCI

Caveats and interpretation

A number of caveats need to be considered when interpreting the results of these analyses. Firstly, the selection of study sites is inevitably constrained by vehicular access. Survey sites on grazing land could be readily accessed using the numerous station tracks; lack of vehicular access limited access to potential sites on nongrazed land. Consequently, grazed sites are biased towards first and second order streams, whereas unimpacted sites are not well represented by small streams. Secondly, the fish data was analysed using a predictive model derived from a large set of regional reference sites spanning the range of aquatic habitats in the catchment, using both boat-mounted and backpack electrofishing methods. Testsite data analysed in this study was predominantly derived from backpack electrofishing of wadeable stream sections, and the fish community may be underestimated. Thirdly, the predictive model used to derive O/E indices is an early dry-season edge habitat model. Macroinvertebrate data in this study was collected in the mid to late dry season, and the predictive model may not be appropriate. Lastly, sampling procedures for chironomid pupal exuviae could not be rigorously standardised.

11.6.3 Results

Biotic data

Data for each of the three biotic indicators is presented in Appendices 13.9, 13.10 and 13.11. The number of taxa, and minimum and maximum number of taxa per site for each indicator group, is shown in Table 11.8.

Table 11.8: Number of taxa and minimum and maximum number of taxa per site.

Indicator	No. of taxa	Min. # taxa per site	Max # taxa per site
Fish	23	4	17
Chironomid pupal exuviae	72	6	29
Macroinvertebrates	133	24	57

Environmental data

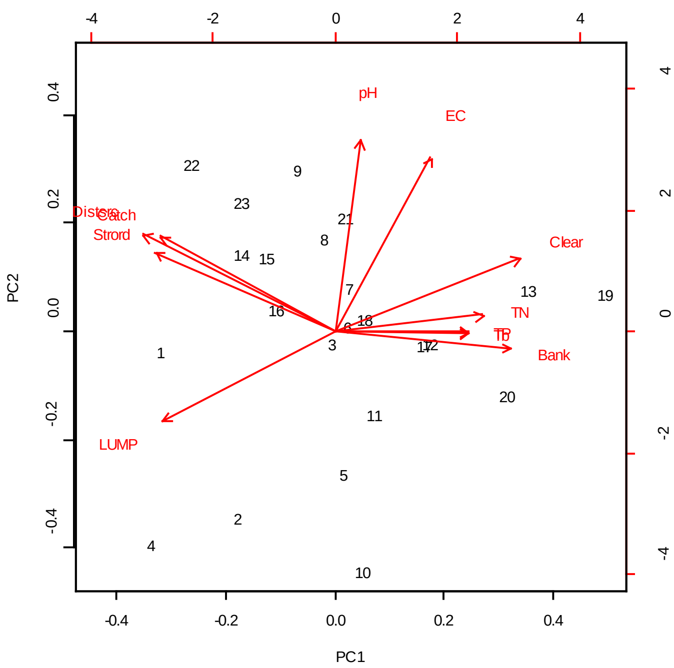
Environmental data used in statistical analyses is presented in Appendix 13.12.

Statistical analyses

Principal components analysis

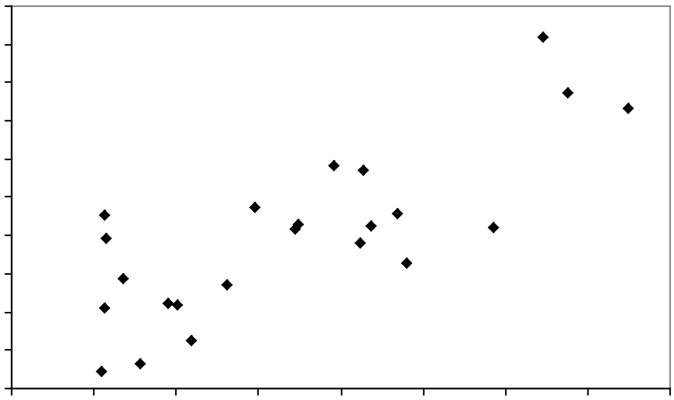
The first two principal components explained >60% of the variance in the data. (PC1 = 43.2%, PC2 = 17.6%). A scatter plot of the sites overlain by vectors for environmental variables revealed that PC1 is positively aligned with disturbance variables, including cattle bank index and %clearing, but negatively aligned with variables describing landscape position. PC2 is aligned with water quality variables pH and conductivity (Figure 11.15).

Figure 11.15: PCA plot showing distribution of individual sites in relation to environmental variables. Site numbers do not correspond to site names.



Further evidence of an association with PC1 and disturbance is seen in Figure 11.16, with PC1 plotted against %clearing.

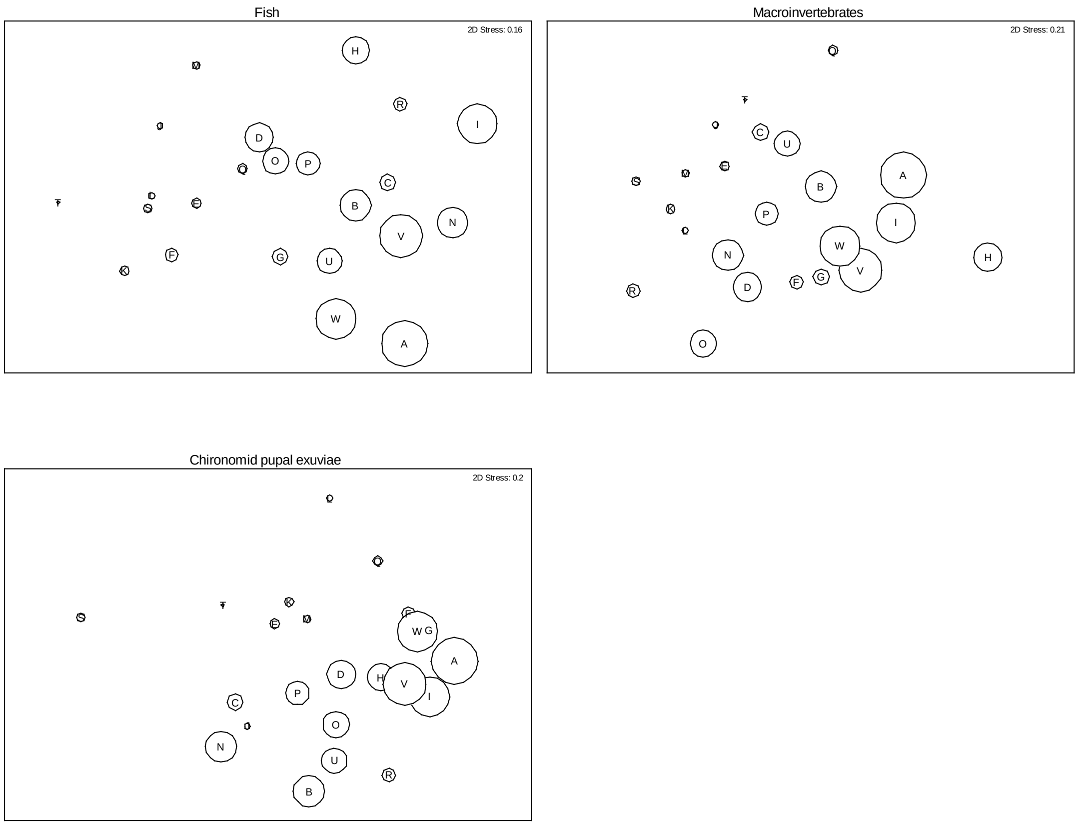
Figure 11.16: Plot of variable %clearing and PC1.



Multivariate analysis of biotic assemblages

Scatter plots of MDS ordinations of presence data for each of fish, macroinvertebrates and chironomid pupal exuviae overlain by bubble plots of catchment size suggest that catchment size is a correlate of assemblage structure in each group (Figure 11.17). Individual sites are coded by lettering common to all plots.

Figure 11.17: Scatter plots of MDS ordinations using presence–absence data for fish, macroinvertebrates, chironomid pupal skins overlain by bubble plots of catchment size.



The relationship between community structure and extrinsic variables in each group was examined using the BIOENV procedure in the software package PRIMER. The BIOENV procedure seeks to identify the best explanatory variables of assemblage structure.

Variables associated with catchment size are listed in sets of best predictors for all biotic indicators (Table 11.9). The variable, distance from source, was present in all three sets. This suggests that landscape position exerts a strong influence on the composition of faunal assemblages.

Table 11.9: Predictor variables correlated with community data from BIOENV procedure.

Biotic indicator	Correlation coefficient	Predictor variables
Fish	0.517	Distance from source Catchment area
Chironomid pupal exuviae	0.454	Stream order Distance from source Catchment clearing Electrical conductivity Turbidity
Macroinvertebrates	0.352	Stream order Distance from source Catchment area Total phosphorus

The procedure RELATE in the software package PRIMER was used to evaluate the similarity between multivariate data sets by calculating a rank coefficient correlation between pairs of biotic indicators. All data was transformed to presence–absence data.

Results indicate low but statistically significant similarity between most datasets. For example, the resemblance matrix for chironomid pupal exuviae data was significantly correlated with resemblance matrices for macroinvertebrates (0.1%), chironomid larvae (0.6%) and approached significance for fish (5.6%) (Table 11.10).

Table 11.10: Results of RELATE procedure matching resemblance matrices of community data.

Indicators	rho	Significance level
Macroinvertebrates vs chironomid pupal exuviae	0.324	0.1%
Fish vs macroinvertebrates	0.162	3.0%
Fish vs chironomid pupal exuviae	0.136	5.6%

Generalised linear modelling

Generalised linear modelling was conducted on two sets of candidate models to examine relationships between landscape disturbance and biotic indicators. The dependent variables were 1) fish model O/E; 2) fish species richness; 3) macroinvertebrate model O/E; and 4) chironomid pupal richness. Model results for set 1 are shown in Appendix 13.13.

Results of modelling provided little support for the hypothesis that biotic indicators responded to measures of landscape disturbance for three of four indicators. The preferred model for fish O/E was indistinguishable from the null model. In contrast there was a reasonably well-supported model for fish species richness, though the preferred model included both PC1 and PC2 and indicates species richness may be determined by several factors, including landscape position, landscape disturbance and water chemistry. The preferred model for macroinvertebrate O/E included the term PC1 and was not strongly differentiated from the null model. Similarly, the preferred model for chironomid species richness included the terms PC1 and PC2, and was not strongly differentiated from the null model.

Model parameters of preferred models (with the exception of unsupported Fish model O/E) for set 1 are shown in Tables 11.11–11.13. The relationships between PC1 and three indicators are shown in Figure 11.18. In each case modelled results suggest a negative relationship; however data is variable and the explanatory variable is confounded by catchment size.

Table 11.11: Model parameters of preferred model for fish richness.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	9.83	0.50	19.59	<0.001	***
PC1	-0.84	0.24	-3.56	0.002	**
PC2	0.97	0.37	2.64	0.016	*

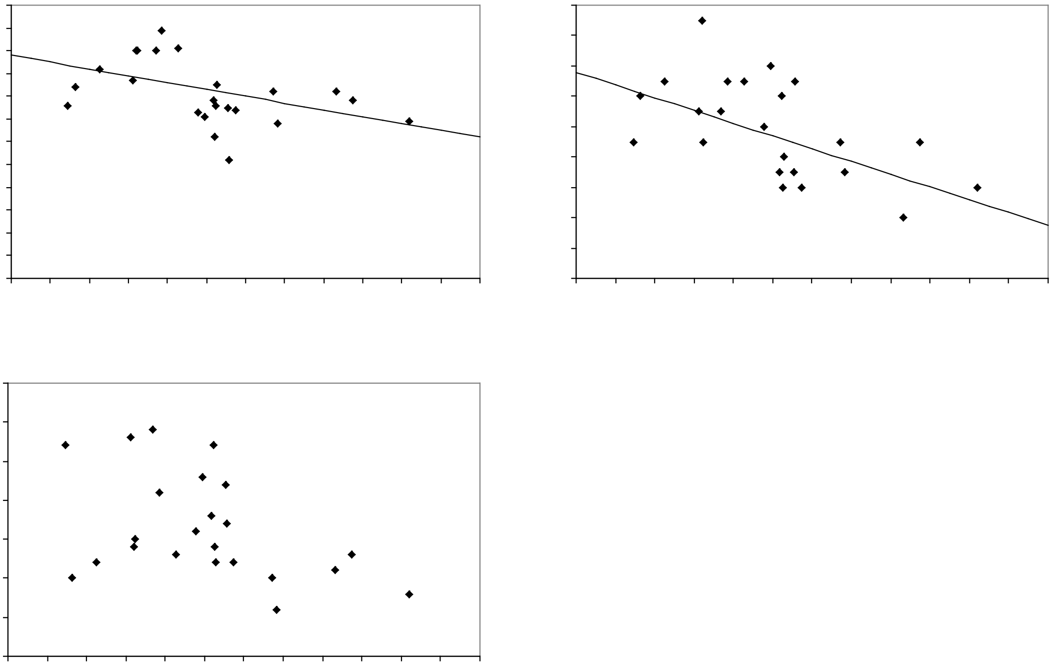
Table 11.12: Model parameters for preferred model for macroinvertebrate O/E.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	0.83	0.03	28.32	<0.001	***
PC1	-0.03	0.01	-2.28	0.033	*

Table 11.13: Model parameters for preferred model for chironomid pupal richness.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	2.78	0.08	34.69	<0.001	***
PC1	-0.08	0.04	-2.00	0.059	.
PC2	-0.09	0.05	-1.86	0.078	.

Figure 11.18: Relationships between PC1 and three indicators. Modelled trends shown where terms in preferred model are significant. Model predictions from significant terms in preferred model shown



Results of modelling using the predictive variables RDI, %clearing and catchment area and cattle bank-access index yielded weak models and provided little support for the hypothesis that biotic indicators responded unambiguously to measures of landscape disturbance (Appendix 13.13). The preferred model for fish O/E was indistinguishable from the null model ($0<x<2$), and is thus very weakly supported. The preferred model for fish richness is well differentiated from the null model and explains 41% of the model variance with the terms catchment area and bank disturbance index, but alternative models containing single terms for bank disturbance index and catchment area have similar levels of support. The preferred models for both macroinvertebrate O/E and chironomid pupal richness are not well supported.

Model parameters of preferred models for set 2 are shown in Tables 11.14–11.17. Scatter plots of data for four biotic indicators and two measures of disturbance, RDI and bank cattle index, are shown in Figures 6–7. Model predictions for those preferred models that include reach disturbance index (fish O/E and chironomid pupal richness) are shown.

Table 11.14: Model parameters for preferred model for fish O/E.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	0.83	0.08	9.85	<0.001	***
RDI	-2.03	0.96	-2.11	0.047	*

Table 11.15: Model parameters for preferred model for fish richness.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	10.59	0.65	16.24	0.000	***
Catch	2.83	1.65	1.72	0.101	
Bank	-1.20	0.61	-1.98	0.062	.

Table 11.16: Model parameters for preferred model for macroinvertebrate O/E.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	0.86	0.03	28.71	<0.001	***
Catch	0.19	0.07	2.77	0.011	*

Table 11.17: Model parameters for preferred model for chironomid pupal richness.

Model parameter	Estimate	Std error	t value	Pr(>|t|)	Sig.
Constant	3.38	0.24	14.31	<0.001	***
RDI	-7.25	3.06	-2.37	0.028	*

Figure 11.19: Scatter plots of relationship between biotic indicators and reach disturbance. Model predictions from significant terms in preferred model shown.

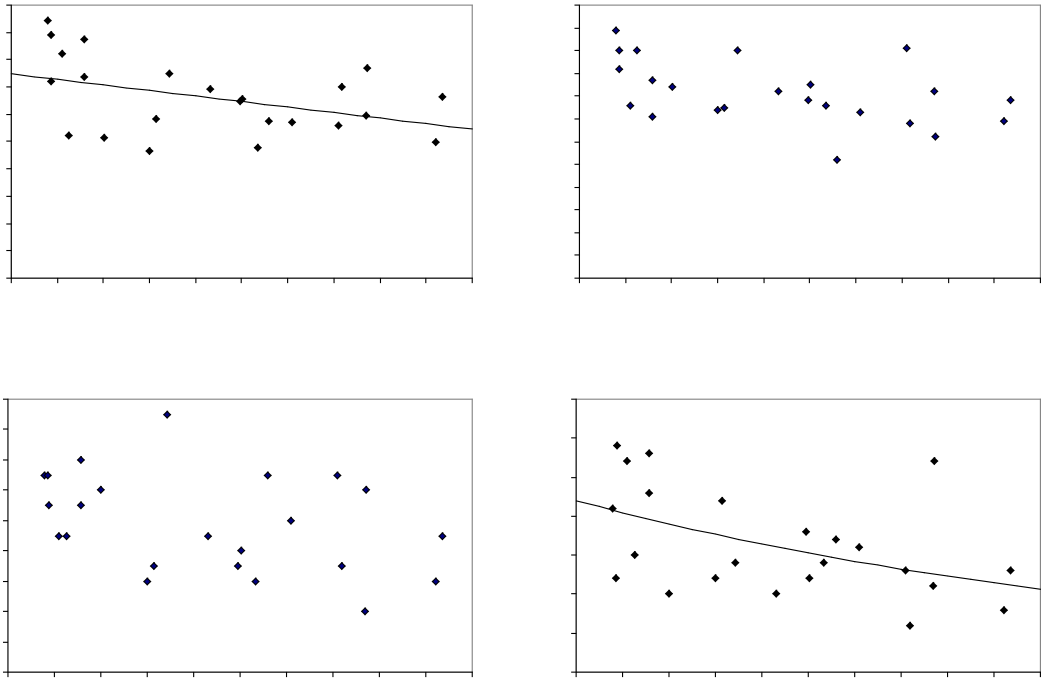
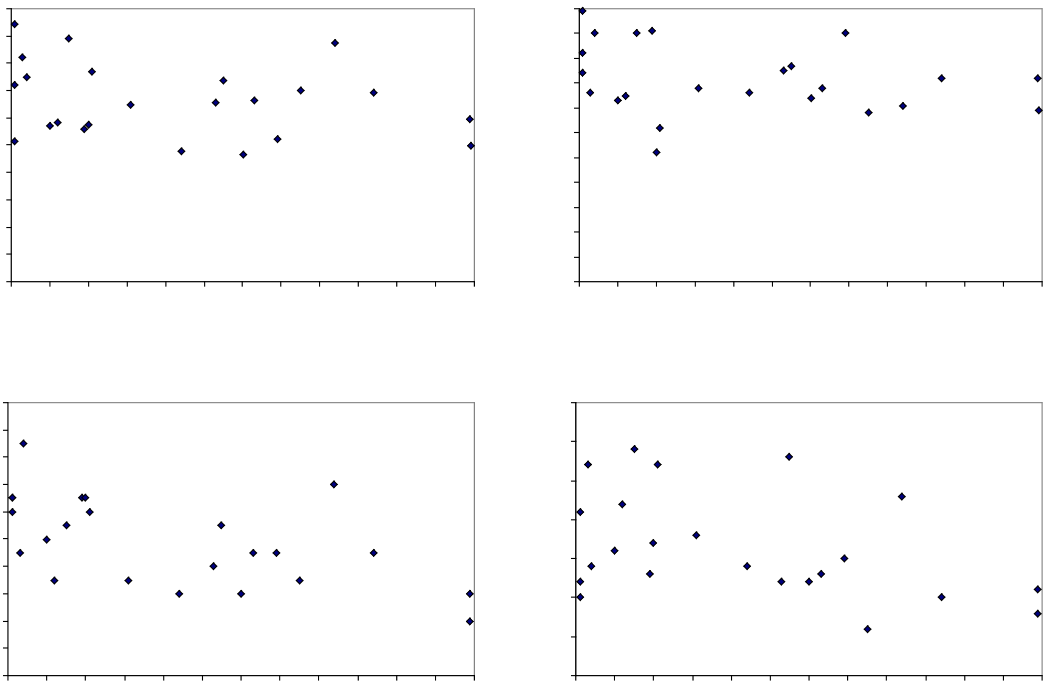


Figure 11.20: Scatter-plots of relationship between biotic indicators and Bank cattle index.



11.6.4 Discussion

Modelling failed to provide unambiguous evidence that any of four biological indicators (fish community structure, macroinvertebrate community structure, fish richness and chironomid richness) responded to a gradient of disturbance. Potential explanations for these results include deficiencies in study design, predictive models, quantification of the disturbance gradient and fauna tolerance.

Small sample size and the low representation of sites located in undeveloped subcatchments influenced to these results. The savannas of northern Australia have been grazed continuously since the late 1800s and few streams are free from at least low levels of impact from feral and domestic herbivores. This is particularly true in land systems with relatively fertile soils and which are favoured by pastoralism, and finding matching sites in similar but ungrazed land systems is rarely possible.

Deficiencies in the performance of predictive models in low-order streams may also have contributed. Low overall fish-taxon richness may bias model predictions (Kennard et al. 2006); for macroinvertebrates low-order streams were not well represented in the reference data used to derive the predictive models (three of 114 reference sites were first-order streams). It may be that the models were insensitive to moderate impacts. Potentially, the inclusion of additional disturbance measures may have strengthened the modelling.

Lastly these streams are occupied by a resilient and generalist fauna that may not challenged by moderate levels of disturbance by grazing within partially cleared landscapes. Further work may be required on a longer gradient of disturbance within sites matched by land systems and landscape position.

11.7 Literature cited

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11.8 **Fitzroy River catchment**

11.8.1 Sensitivity of water quality to impacts of cattle grazing

The effects of cattle access to riparian zones and surface water represents one of the key disturbances in the Fitzroy catchment. Cattle access to these areas is largely unmanaged (unfenced) throughout most of the catchment except in the upper reaches, where stocking rates have progressively been reduced over the last 10 years on Mornington Station. Several sites on the Fitzroy River and lower reaches of major tributaries including the Hann, Adcock and Traine rivers have now been largely destocked for several years.

Several metrics of cattle disturbance were trialled during the FARWH field survey,s including the three metrics used in the Daly River trials described above: density of cattle tracks, bank access and trampling. Unfortunately, a high level of uncertainty surrounded quantification of these metrics in the Fitzroy catchment, and they proved inappropriate for the determination of a cattle disturbance gradient for the following reasons:

1. Although distinct tracks could sometimes be identified in the riparian zone, their use by cattle was difficult to determine. In many cases, no clear evidence of cattle use of tracks (e.g. hoof marks) could be identified.
2. Due to the steep banks of the river channel, few potential cattle access points were identified. Where potential access points were identified, their use by cattle was difficult to determine, but in most cases, was thought to be low owing to the steep banks.
3. Most cattle appear to access wider sections of the river channel where the banks were low and the gradient less steep. As sampling for FARWH indices was generally undertaken in permanent pools, where the river channel was constrained by steeper banks, most of these cattle access points fell outside of the sampling site boundaries.
4. Very few cattle were observed in the riparian zone or in the river channel during field surveys.

Instead, cattle disturbance was assessed subjectively, based on observation of potential cattle use (tracks, cow pads, access points and trampling) and where possible, from information provided by traditional owners and station managers on the distribution of cattle, their use of the river channel and recent pastoral management. Sites were assigned to one of four categories of cattle disturbance; none, low, moderate and high (see Figure 11.21). We also investigated the response of water quality parameters to the pressure/condition gradient used to identify reference sites, discussed in Chapter 6.

Figure 11.21: Examples of the range of cattle grazing categories in the Fitzroy River catchment. The left photo shows a site with no cattle disturbance, located within the destocked area of Mornington Station. These sites had no obvious cattle tracks, river access points or grazing of either tree seedlings or understory grasses. The right photo shows a site with 'high' cattle disturbance. These sites had numerous tracks, access points and there were signs of intense grazing within the riparian corridors

11.8.2 Response of indices to cattle disturbance bands

We examined the response of turbidity, nutrients, dissolved oxygen, pH and macroinvertebrate O/E values to a cattle disturbance, and pressure/condition gradient (Figure 11.22 and 11.23), as these parameters were assumed to be most sensitive to cattle effects. Regression analysis indicated none of the water quality parameters showed a significant response (alpha = 0.05) to the pressure/condition gradient (Figure 11.22a). Total nitrogen, phosphorous and turbidity were all lower and less variable at destocked sites located on Mornington Station compared with sites impacted by low, moderate and high cattle disturbance. For each of these parameters, measurements tended to be highly variable for all other categories of cattle disturbance and no clear response with increased disturbance could be identified. There was no clear relationship between pH values with either the pressure/condition gradient or the cattle disturbance categories.

The insensitivity of water quality attributes to both the pressure and condition index and to cattle disturbance gradients highlights the need to undertake further investigation on the natural temporal and spatial variability of water quality within the Fitzroy catchment. More detailed knowledge of this kind will allow reassessment of condition bands and the establishment of appropriate reference conditions for each parameter in future assessments of river health.

Macroinvertebrate O/E scores showed a clear response to both pressure/condition index and cattle disturbance categories (Figure 11.23). Macroinvertebrate O/E scores were positively correlated with the pressure condition index, and negatively correlated with the cattle disturbance gradient. While this finding is interesting, interpretation of the response of macroinvertebrates to changes in environmental conditions is difficult to interpret.

Figure 11.22: Relationships between turbidity, total nitrogen, total phosphorous and pH raw data and a) pressure disturbance gradient and b) cattle disturbance categories in the Fitzroy River. Symbols and abbreviations denote cattle disturbance categories as: A, absent; L, low; M, moderate and; H, high

(a) (**b)**

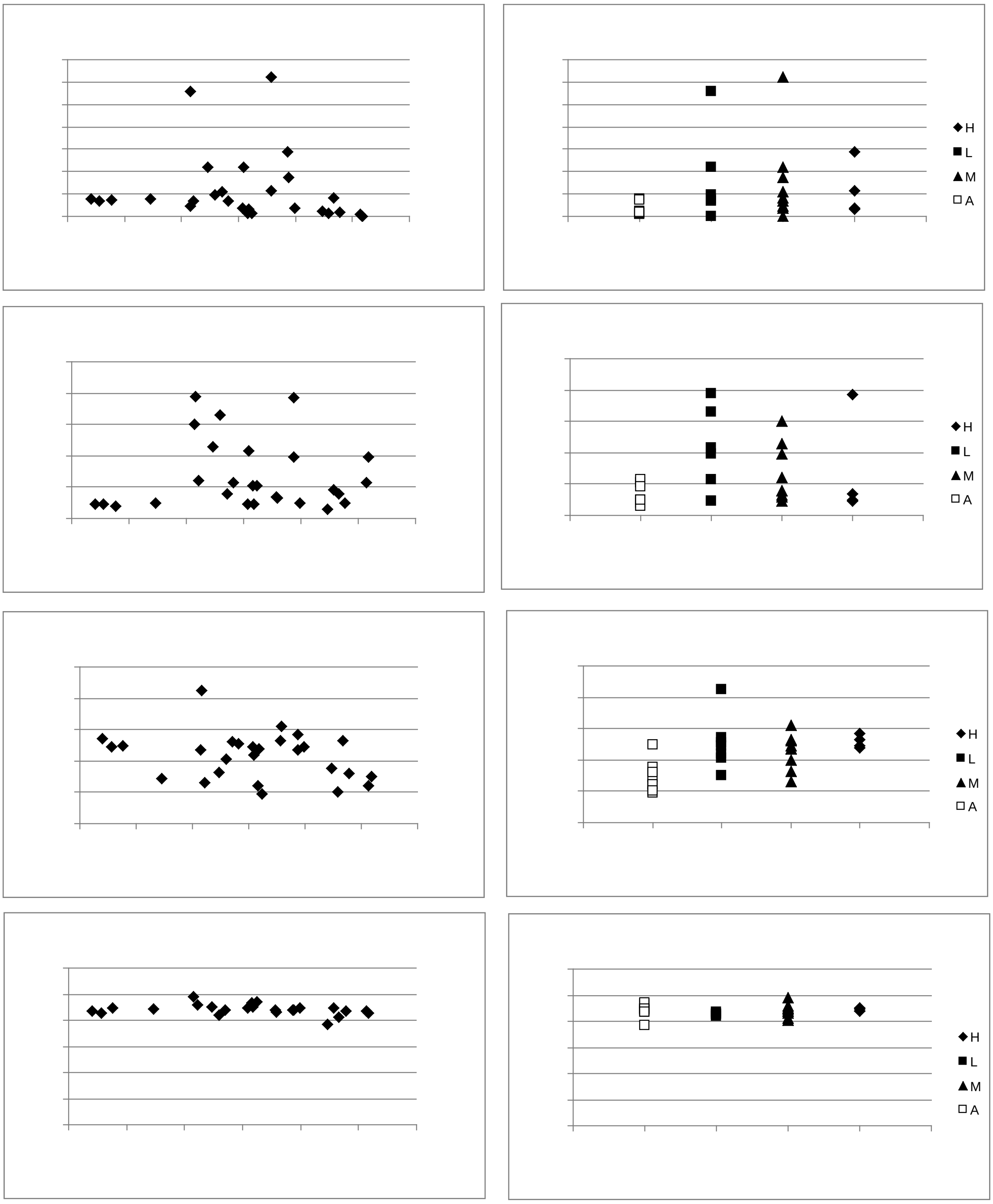
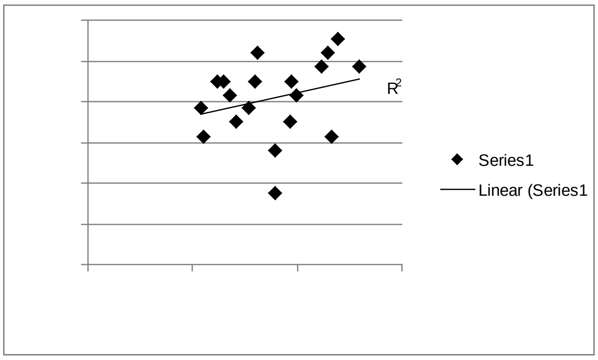
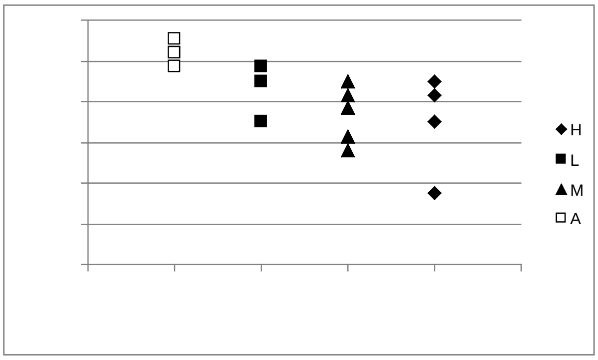


Figure 11.23: Relationships between macroinvertebrate O/E score and pressure/condition and cattle disturbance categories. Symbols and abbreviations denote cattle disturbance categories as: A, absent; L, low; M, moderate and; H, high





11.8.3 Sensitivity of fish O/E scores to recreational (including traditional owner) fishing pressure

As discussed previously, aquatic ecosystems may be influenced by their surroundings at a variety of scales (Hunsaker and Levine 1995; Allan 2004). Human impacts on local assemblages are likely to be scale dependent, potentially being affected by processes operating at both landscape scales (e.g. agricultural runoff from upstream areas and barriers downstream) and local scales (e.g. riparian and in-stream habitat degradation, fishing pressure), a concept demonstrated in practice by many studies (e.g. Roth et al. 1996; Allan et al. 1997; Stauffer et al. 2000, Allan 2004, Kennard et al.. 2006).

The sensitivity of the fish O/E score was investigated using both the pressure/condition index and an index of local fishing pressure (Figure 11.23). Sites were assigned to four categories of fishing pressure (none, low, moderate and high) based on observed fishing activity made during the field trials, and based on discussions with traditional owners who identified the importance of individual sites for local fishing activities.

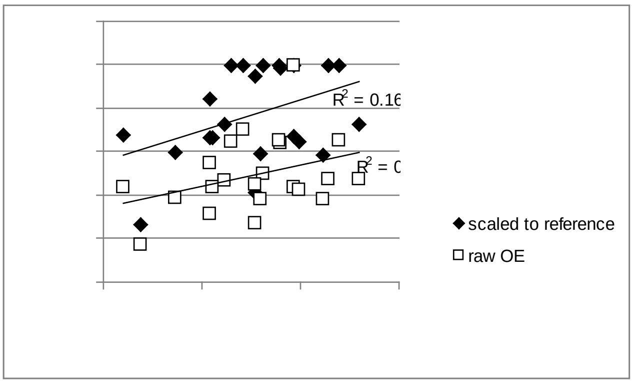
Both the reference standardised and unstandardised fish O/E scores showed a significant relationship to the pressure/condition score (Figure 11.24). Similarly, the unstandardised O/E score showed a clear, decreasing trend with increasing fishing pressure. A less distinct trend was apparent for the reference standardised O/E score, although scores tended to decrease and become more variable as fishing pressure increased.

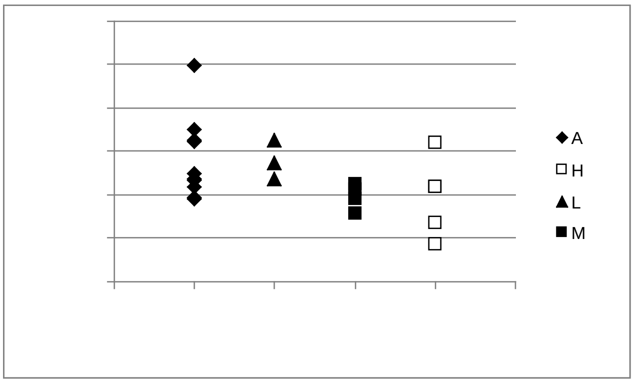
Because fish can integrate human disturbances arising from multiple sources at a range of spatial and temporal scales, they are considered useful indicators of environmental change. However, the existence of multiple, scale-dependent mechanisms, the potentially nonlinear responses of biota to disturbance, and the difficulties of separating current from historical effects can make it difficult to establish relationships between disturbance and ecosystem health indicators or to diagnose the specific sources or mechanisms of human impact (Allan 2004).

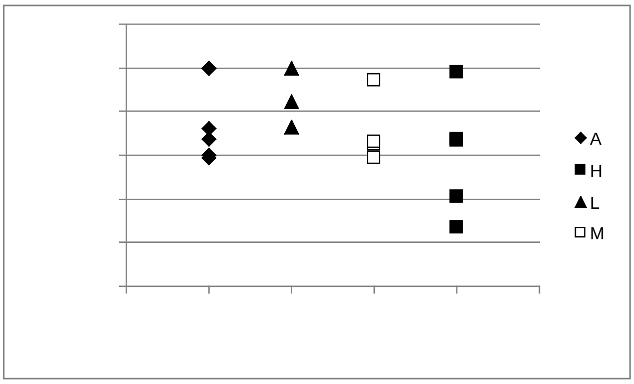
The FARWH trials presented here have relied on presence–absence data and O/E scores. Although some relationships to condition of sites and fishing pressure have been identified, the sensitivity of the fish index is likely to be constrained by the use of a presence–absence model. A response in the index will only occur at the point of collapse, i.e. when sites can no longer support species populations. Furthermore, given the precautionary approach for establishing reference conditions, using broad distributional data, it is difficult to interpret whether a change in the fish O/E score can be attributed to a change in environmental conditions, or fishing pressure, or whether it is simply responding to interannual variability in the distribution of species. For example, many of the fish species inhabiting the Fitzroy River are distributed along (almost) the entire length of the catchment. Many species are migratory (diadromous, potadromous), and thus their distribution is likely to be influenced by antecedent flow events (particularly wet season flows) that facilitate longitudinal and lateral movements in and from the main river channel. Given these uncertainties, it is difficult to interpret any change in the fish O/E score.

Based on these observations, further investigation of sensitive fish indices should be undertaken. A range of other possible fish indices have been trialled in other river health assessments, including the Index of Biotic Integrity, the Sustainable Rivers Audit, and the Index of Stream Condition. Many of these indices required specific ecological knowledge to assign species to trophic, habitat or reproductive guilds. Quantitative knowledge of this kind is generally insufficient to apply similar indices to fish assemblages in the Daly and Fitzroy river catchments. Alternatively, indices that include information on population (size structure) and reflect variations in spawning and/or recruitment success may represent sensitive indices for future assessments.

Figure 11.24: Relationships between standardised and nonstandardised fish O/E scores and pressure/condition and fishing pressure categories. Symbols and abbreviations denote fishing pressure categories as: A, absent; L, low; M, moderate and; H, high







11.8.4 Literature cited

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Stauffer JC, Goldstein RM and RM. Newman 2000, 'Relationship of wooded riparian zones and runoff potential to fish community composition in agricultural streams,'. *Canadian Journal of Fisheries and Aquatic Sciences*. 57: 307–316.

Kennard MJ, Pusey BJ Arthington, A.H, Harch BD. and Mackay SJ 2006,. ‘Development and application of a predictive model of freshwater fish assemblage composition to evaluate river health in eastern Australia’, *Hydrobiologia* 572: 33–57.

12 Overall discussion

12.1 Discussion and recommendations

This report has summarised the trials of the FARWH in two catchments of northern Australia: the Daly River (NT) and the Fitzroy River (WA). In addition to trialling the framework, field methods and data analyses, this report presents an investigation into the sensitivity of indicators of river health to a gradient of localised pressures; especially land use, and cattle and feral animal activity. In the study catchments, and in the wet/dry tropics generally, disturbances to river health are less intensive and the health of rivers generally higher than in temperate Australia. At the core of the FARWH is the use of indicators that respond to anthropogenic impacts. Although the cattle disturbance gradient studies included sites of perceived high impact, they revealed that the sensitivity of riparian and aquatic biota indicators to cattle disturbance were variable. This may be due to either the low level of impact or the lack of indicator sensitivity. It emphasises that indicator sensitivity needs to be understood, along with their thresholds of detection.

Consequently, a primary objective of river health monitoring in the wet/dry tropics should be the early detection of river health degradation. Early detection will provide managers more opportunities to mitigate further degradation through adoption of a *prevention* rather than *restoration* philosophy to river health management. This has significant implications for the application of river health monitoring for the wet/dry tropics, and FARWH specifically.

A key recommendation from this study is for further development of appropriate indicators and their scoring that will allow for the early detection of river health degradation. The use of indicators with high detection thresholds (i.e. those that are insensitive) in future FARWH assessments would not permit early detection of river health degradation. This would be less suitable for river health assessment in the wet/dry tropics. We recommend that future FARWH assessments be preceded by studies that provide information about indicator responsiveness and thresholds to anthropogenic disturbances.

The early-detection objective reflects the benefits associated with the ability to identify small changes from reference condition. This in turn emphasises the requirement for sound knowledge on reference conditions and their relationship to test sites. For these FARWH trials, reference conditions were poorly understood for the water quality, physical form, fringing zone and aquatic biota (fish subindex) themes and therefore constrained the calculation of FARWH scores. The best reference data available was for macroinvertebrates in the Kimberley and Darwin–Daly regions, which forms the basis of the AUSRIVAS predictive model. However, the AUSRIVAS reference data set for the Darwin–Daly region mainly represented middle and higher order rivers; low-order streams, most vulnerable to cattle disturbance, were poorly represented and the model may not predict reference condition for these sites accurately. Future FARWH assessments need to select appropriate reference sites relevant to test sites.

The need to detect small changes in river health will require a greater sampling effort in order to minimise Type I errors; the conclusion that river health is in reference condition but is instead impacted, albeit at a low level. The huge size of the SWMA also necessitates greater sampling effort to provide a reasonable spatial coverage of sampling sites. In combination, these constraints are likely to result in the requirement to sample an unrealistic number of sites at the SWMA scale. Instead, we recommend that future FARWH assessments focus on subcatchments of the SWMAs.

Sample site selection in wet/dry tropical catchments needs to contend with remoteness, difficulty of physical access, requirements for landholder permission and participation, contrasting seasonal river conditions and, sometimes, poor river knowledge (such as the persistence of dry season flows). Together, these constraints make it impractical to select sites randomly, as recommended by FARWH.

River health was assessed for perennial flowing rivers or permanent pools in the dry season. This was, for both, the practical reason of accessibility and because river health tools (e.g. AUSRIVAS) were only applicable to the dry season. Nonetheless, high flows during the wet season are critical in determining biophysical conditions in these catchments. High flows determine channel morphology as well as the diversity and abundance of aquatic habitats. Inundation of riparian and floodplain habitats during these events also influences conditions in floodplain wetlands and the recruitment of riparian vegetation. Many biological processes, such as fish recruitment and carbon cycling, which are critical to the health of rivers, are also supported by the seasonal inundation of riparian and floodplain habitats. As such, river health assessment needs to be extended to include the wet season where possible. We recommend that wet season river connectivity to floodplains and wetlands, and a simple assessment of their condition (e.g. grazed or not grazed) should be included in future FARWH assessments.

In the trial catchments of the wet/dry tropics, theme scores were not calculated with equal confidence and varied with respect to their comparison with reference condition. If management decisions and resources are dependent on the FARWH scores, there needs to be a rating of their accuracy, even if it is a simple descriptive rating of high, medium, low. For example, the water quality theme scores were based on broad ranges and require further development. We therefore recommend future FARWH assessments include a rating of theme accuracy or confidence.

FARWH aggregates the five themes using the recommended Euclidean distance approach. While mathematically appealing, this level of mathematical sophistication is not matched by the simpler FARWH theme calculations. Instead, a mean score of the FARWH themes is recommended, for consistency of mathematical sophistication and to promote easy communication of the FARWH results.

The primary recommendation of this trial is that a two-tiered approach be undertaken for assessing river health in SWMAs of the wet/dry tropics. The first tier can be achieved at the SWMA scale and would assess catchment disturbance, using spatial data sets, supported by ancillary information such as cattle stocking rates and the number of significant point sources of pollution (e.g. mine and sewage discharges). This would provide an assessment of catchment-scale pressures on river health. The second tier would comprise river health case studies that include appropriate reference sites. In addition to providing FARWH scores, these case studies could have an experimental design that would assist in data interpretation to evaluate the extent and nature of river health disturbance. This tier would provide site/reach scores for the water quality, physical form, fringing zone and aquatic biota themes and possibly for the hydrology theme. These case studies would provide early warning of river health degradation, and be undertaken in the context of catchment-wide pressures on river health. Based on the relationship between the disturbance and river health degradation, the results from the case studies could be extrapolated to the SWMA to be combined with the catchment disturbance theme for a FARWH SWMA score.

In summary, the following eight general recommendations are made for future FARWH assessments in the wet/dry tropics:

1. The overarching philosophy should be *prevention* rather than *restoration.*

2. The overarching monitoring objective should be for *early detection* of river health degradation.
3. Reference conditions require further investigation and understanding if a referential approach is to be used appropriately.
4. Further testing and investigation of indicator responsiveness and sensitivity to low-level disturbance to identify suitable indicators.
5. Wet season river health should be incorporated into river health monitoring.
6. Uncertainty and/or reliability should be clearly documented in setting reference conditions, using predictive or subjective techniques.
7. Integration methods to communicate final FARWH scores should be reconsidered.
8. A two-tiered approach that accounts for both SWMA-scale reporting and smaller scale monitoring and investigation be adopted.

12.2 **Capacity building and training**

The eWater Education and Training Team, University of Canberra, was contracted by the TRaCK FARWH program to provide a demonstration FARWH communication and training website. The website provides trial tools and products needed to roll out FARWH for tropical northern Australia. The website has three primary objectives:

- educate the general public about the FARWH.
- provide comprehensive and user-friendly access to FARWH scores and maps
- provide structured training on FARWH methods to facilitate on-going

assessment by Agency staff and volunteers.

The public website will broadly outline current issues in river health and the ecological response of rivers to disturbance. The background and purpose of the FARWH will also be outlined. Background information is included so that website users understand the scientific review process used to develop FARWH methods, and to aid in interpretation of scores and indices. From the public website, users can access all FARWH scores and indices for tropical northern Australia. Mapping and publication of FARWH results is being developed using a customised mapping engine with spatial and database-oriented analysis techniques that will help users view and interpret the data. Results are presented via a regional map. From this broad scale users can drill down to view results in specific catchments and reaches of interest. Accompanying the map view, users can access associated charts and tables that provide more detail on the individual subindices and component scores.

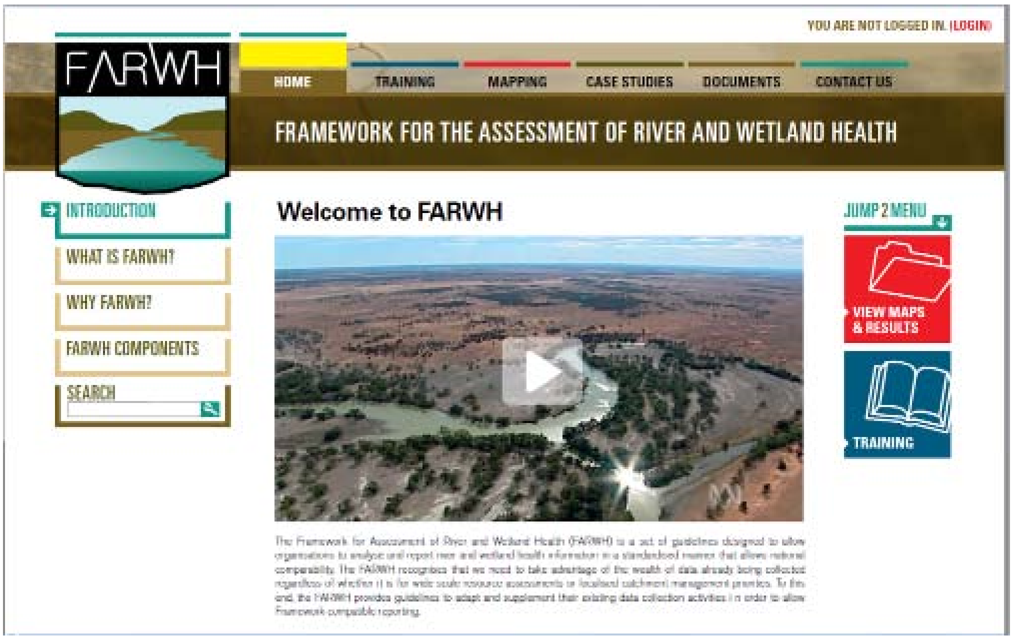
The public website will also be the first point of training for internal and affiliated staff and volunteers. From the public website, agency staff will be able to access a password-protected training website that will include detailed information on FARWH field and desktop methods. The training website will be developed using the Moodle open-source Learning Management System and fully SCORM-compliant eLearning software. Training website access and administration will be under agency control. The training is divided into a series of 11 modules that will allow users to train in some or all FARWH methods. Individual modules include the six FARWH themes (e.g. hydrological disturbance, catchment disturbance); reach and site selection; generating indices and data analysis; and reporting. A sample image from the concept design is presented in Figure 12.23.

From the public website, users will be able to access all FARWH scores and indices for tropical northern Australia. Mapping and publication of FARWH results is being developed using a customised mapping engine with spatial and database-oriented analysis techniques that will help users view and interpret the data. Results will initially be presented via a regional map. From this broad scale users can drill down to view results in specific catchments and reaches of interest. Accompanying the map view, users will be able to access associated charts and tables that provide more detail on the individual subindices and component scores. It is intended that users will be able to create customised maps and reports in PDF format.

The public website will also be the first point of training for internal and affiliated staff and volunteers. From the public website, agency staff will be able to access a password-protected training website that will include detailed information on FARWH field and desktop methods. The training website will be developed using the Moodle open-source Learning Management System and fully SCORM-compliant eLearning software. Training website access and administration will be under agency control. The training is divided into a series of 11 modules that will allow users to train in some or all FARWH methods. Individual modules include the six FARWH themes (e.g. hydrological disturbance, catchment disturbance); reach and site selection; generating indices and data analysis; and reporting.

The FARWH training and communications website is due to be completed in August 2010. A sample image from the concept design is presented in Figure 12.

Figure 12.23: Draft design for FARWH training and communications website.



12.3 **Costing**

Costing for FARWH assessment in the wet/dry tropics.

The design recommended for FARWH monitoring comprises two components. The first would be an assessment of catchment condition, using the HDI and the CDI but supplemented by other information such as point-source pollution assessments from mines and wastewater treatments plants and stock and feral animal numbers. This index would not be undertaken for the full catchment, rather but on a subcatchment basis selected primarily for their management significance. It would provide an assessment of the pressures in the catchment.

The second component would be an assessment of the other FARWH themes, but undertaken at sites selected, based on an experimental design that would seek to detect impact from anthropogenic nonpoint source disturbances. For the purposes of the costing, 20 sites would be sampled, twice in the dry season. The sites would be assessed for the remaining FARWH themes. The selection of the sites needs to be strategic and done in the context of the full catchment to allow an extrapolation to the wider catchment if required.

Single catchment costs (for both components 1 and 2):

- Field days: (20 sites, twice during the dry season): 400 field person days.
- Office support (e.g. data collation and analysis), laboratory days and reporting: 250 person days.
- Assuming a daily cost of $1000, this approximates $650 000 for labour.
- Operational costs (vehicle hire, water analyses, travel allowance, equipment hire): $100 000.
- Total cost: **$750 000 per catchment.**

This cost does not include research required to improve the FARWH metrics, nor the selection of sites (and sample design), which can be time consuming. Also, it does not include administrative support and supervision by state agencies.

Monitoring frequency and catchments

Four catchments are recommended for monitoring. These are the Ord River and Darwin Harbour catchments, because they have subcatchments of high intensive land use (notably agricultural and urban),;the Daly catchment, which has agricultural and pastoral land uses, as well as consumptive water uses; and the Fitzroy River, where cattle grazing in extensive. The Roper catchment in the Northern Territory warrants consideration because of its substantial groundwater resources and increasing development pressures. This is a small proportion of the total area of the wet/dry tropics in the Northern Territory and Western Australia, but is intended to keep the monitoring focused and provide information about land use and other impacts on wet/dry tropical river health that can be extrapolated elsewhere.

Annual monitoring frequency is recommended in order to detect small rates of river health degradation and to differentiate these from natural inter-annual variability. Four catchments monitored annually would cost $3 million, based on the program outlined above.

13 Appendices

Appendix 1: Field sites for the Daly River SWMA, 2009

Table 13.1: FARWH site descriptions and locations in the Daly River SWMA (coordinate system WGS 84). GCODE = NRETAS site labelling system.

FARWH Site	Site description	GCODE	LATITUDE	LONGITUDE
DG01	Douglas River u/s Hayes Creek	G8145419	-13.788109	131.296927
DG02	Douglas River u/s Hot Springs	G8140017	-13.761418	131.471451
DP01	Depot Creek at Butterfly Gorge Rd	G8140018	-13.753822	131.485261
DY01	Daly River at Claravale Crossing	G8145610	-14.363667	131.556455
DY02	Daly River at Oolloo Crossing	G8140038	-14.070904	131.251870
DY03	Daly River u/s Beeboom Crossing	G8140021	-13.862721	131.076026
DY04	Daly River u/s Daly Crossing	G8145770	-13.767488	130.710519
ED01	Edith River d/s of Jabula Rd	G8140035	-14.171390	132.117970
FL01	Flora River d/s of Djurrung Falls	G8145323	-14.757614	131.594701
FL02	Flora River d/s Camp Two	G8145383	-14.668141	131.682764
FP01	Fingerpoint Creek at Claravale Rd	G8140036	-14.077660	131.816921
GA01	Green Ant Creek	G8140037	-13.537133	131.183880
GA02	Green Ant Creek	G8140043	-13.572703	131.203453
GA03	Green Ant Creek	G8140046	-13.614604	131.186184
GA04	Green Ant Creek	G8140047	-13.745230	131.097789
GA05	Green Ant Creek	G8140353	-13.774771	131.099077
GT01	Green Ant Trib.	G8140050	-13.521011	131.201229
GT02	Green Ant Trib.	G8140051	-13.625559	131.185488
GT03	Green Ant Trib.	G8140052	-13.601255	131.140458
GT04	Green Ant Trib.	G8140053	-13.639384	131.109945
HY01	Hayes Creek u/s Douglas River	G8145419	-13.787965	131.296780
HY02	Hayes Creek u/s Blue Hole	G8140054	-13.760525	131.318592
KA01	Katherine River d/s Galloping Jacks	G8140301	-14.548167	132.129500
KA02	Katherine River	-	-14.506687	132.226701
KA03	Katherine River d/s Maud Creek	-	-14.375886	132.399363
KA04	Katherine River	G8140055	-13.761473	133.083195
KA05	Katherine River	G8140056	-13.419926	133.202390
KA06	Katherine River	G8140057	-14.048079	132.729456
KG01	King River u/s Victoria Hwy	G8140064	-14.705146	132.079547
MD01	Middle Creek d/s Oolloo Rd	G8145418	-13.807977	131.339265
ME01	Maud Creek u/s Gorge Rd	G8140065	-14.383588	132.422978
SC01	Scott Creek u/s Victoria Hwy	G8140066	-14.925629	131.877119
SM01	Seventeen Mile Creek	G8140069	-14.298959	132.413654
SN01	Station Creek	G8140070	-13.594489	131.068496
SN02	Station Creek (second cattle crossing)	G8140071	-13.607765	131.049831

FARWH Site	Site description	GCODE	LATITUDE	LONGITUDE
SN03	Station Creek (first cattle crossing)	G8140072	-13.607512	131.044883
SN04	Station Creek Trib.	G8140073	-13.669864	131.079460
SN05	Station Creek at Honeymoon Rd	G8140074	-13.699382	131.058237
ST01	Stray Creek u/s Flemming Rd	G8145749	-14.116669	131.441201
ST02	Stray Creek at Old Ford	G8140075	-14.069640	131.480088
ST03	Stray Creek at Jindare Rd	G8140076	-13.972174	131.644906

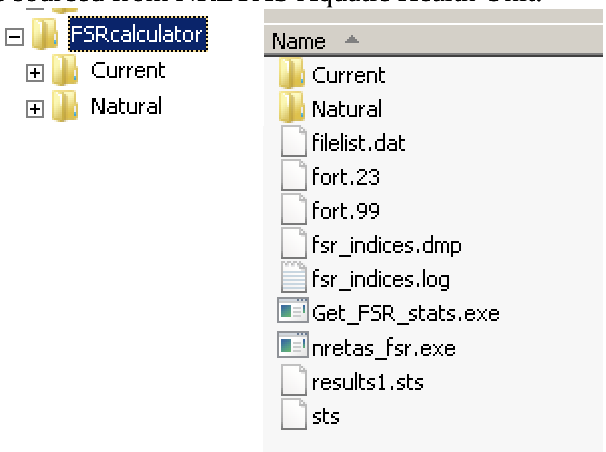
Appendix 2: Field sites for the Fitzroy River SWMA, 2009

Table 13.2: FARWH site descriptions and locations in the Fitzroy River SWMA (coordinate system WGS84).

FARWH Site	Site description	LATITUDE	LONGITUDE
FARWH_1	Fitzroy River Bayulu sandbar # 1	18º 21' 59.2"	125º 29' 46.3'
FARWH_2	Fitzroy River Bayulu sandbar # 2	18º 26' 26.6"	125º 23' 07.1'
FARWH_3	Brooking Creek	18º 11' 0.0"	125º 35' 04.6'
FARWH_4	Fitzroy River Donkey Crossing	18º 14' 23.3"	125º 32' 59.5'
FARWH_5	Fitzroy River at Fitzroy River Lodge	18º 12' 26.2"	125º 34' 55.6'
FARWH_6	Fitzroy River at Geikie Gorge	18º 03' 59.1"	125º 43' 49.2'
FARWH_7	Margaret River at Muludja crossing	18º 09' 14.2"	125º 42' 40.0'
FARWH_8	Fitzroy River–Pandanus Creek confluence	17º 49' 17.6"	125º 55' 47.6'
FARWH_9	Fitzroy River at Noonkanbah Crossing	18º 30' 34.1"	124º 50' 18.9'
FARWH_10	Fitzroy River tributary–Sandy Billabong	18º 27' 04.8"	124º 48' 13.5'
FARWH_11	Fitzroy River downstream of Noonkanbah Crossing	18º 29' 38.4"	124º 46' 30.4'
FARWH_12	Cunningham River at Jubilee Downs	18º 22' 07.1"	125º 18' 04.6'
FARWH_13	Cunningham River downstream of Jubilee Downs	18º 24' 26.1"	125º 15' 25.9'
FARWH_14	Laughter Creek	18º 33' 17.70"	127º 11' 49.78'
FARWH_15	Minnie/Cherabun Creek	18º 34' 11.65"	127º 20' 24.58'
FARWH_16	Christmas Creek	18º 29' 57.71"	125º 25' 14.37'
FARWH_17	Leopold River at confluence with Fitzroy River	18º 15' 08.1"	126º 14' 47.9'
FARWH_18	Margaret River Shady Bore on Fossil Downs	18º 17' 57.04"	126º 00' 13.20'
FARWH_19	Leopold River at Barramundi Pool	18º 03' 35.26"	126º 14' 04.71'
FARWH_20	Margaret River at 'Me No Savvy'	18º 28' 12.3"	126º 34' 59.7'
FARWH_21	Margaret River at 'Mangineooaa'	18º 25' 21.8"	126º 35' 45.8'
FARWH_22	Fitzroy River at Camballin Barrage	18º 11' 18.0"	124º 29' 36.0'
FARWH_23	Mary River at Mary Pool	18º 43' 31.13"	126º 52' 22.83'
FARWH_24	Annie Creek	17º 30' 28.0"	126º 26' 44.9'
FARWH_25	Fitzroy River at Sir John Gorge	17º 31' 49.0"	126º 12' 43.8'
FARWH_26	Fitzroy River at Dimond Gorge	17º 38' 15.0"	126º 02' 19.6'
FARWH_27	Fitzroy River at Bluebush Waterhole	17º 33' 27.2"	126º 10' 11.8'
FARWH_28	Throssell River at Mornington Road crossing	17º 21' 57.7"	126º 05' 47.8'
FARWH_29	Fitzroy River at Cadjeput Waterhole	17º 34' 25.6"	126º 08' 03.8'
FARWH_30	Adcock River Annie Creek confluence	17º 32' 07.0"	126º 06' 38.7'
FARWH_31	Hann River downstream of Tablelands Track crossing	17º 13' 23.1"	126º 16' 23.3'
FARWH_32	Traine River at Tirralinjji Community Pool	17º 11' 36.0"	126º 27' 18.2'
FARWH_33	Traine River tributary at Idlo Waterhole	17º 13' 32.5"	126º 33' 24.8'
FARWH_34	Adcock River on Mt House station	17º 23' 09.2"	125º 54' 33.1'
FARWH_35	Mary River at Mary River Camp	18º 43' 31.13"	126º 52' 22.83'
FARWH_36	Unknown dry stream at Noonkanbah	18º 30' 34.1"	124º 50' 18.9'
FARWH_37	Hann River at 'One Tree Hill	17º 23' 59.15"	126º 17' 25.46'

Appendix 3: Operator Instructions for calculation of FSR using NRETAS_FSR.exe

1. **Copy FSRcalculator folder on computer C:/ drive.** NRETAS_FSR.exe is a small dos executable program and related files provided by Rory Nathan, SKM. The file has been provided to CDU and NRETAS to trial the FSR procedure in the wet/dry tropics. A copy can be sourced from NRETAS Aquatic Health Unit.

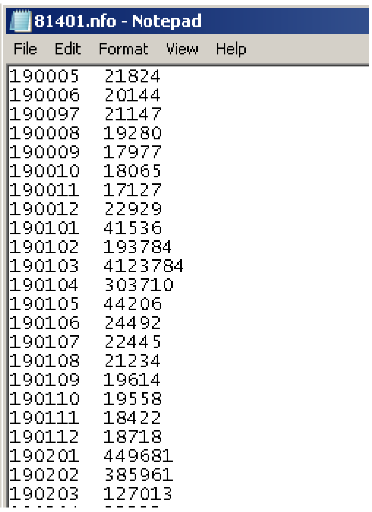


   The most important files for basic operation are 'filelist.dat', 'Current' folder, 'Natural' folder and 'nretas_fsr.exe.'

2. Obtain modelled data for pre- and postdisturbance. Must be concurrent datasets of a minimum of 15 years and start from the same date. This can be provided by a range of rainfall runoff models e.g. SimHyd.

3. Transform data into Total Monthly Flow (ML/month) for time series. This can be achieved using a number of methods. Quickest is using Pivot Tables in Excel.

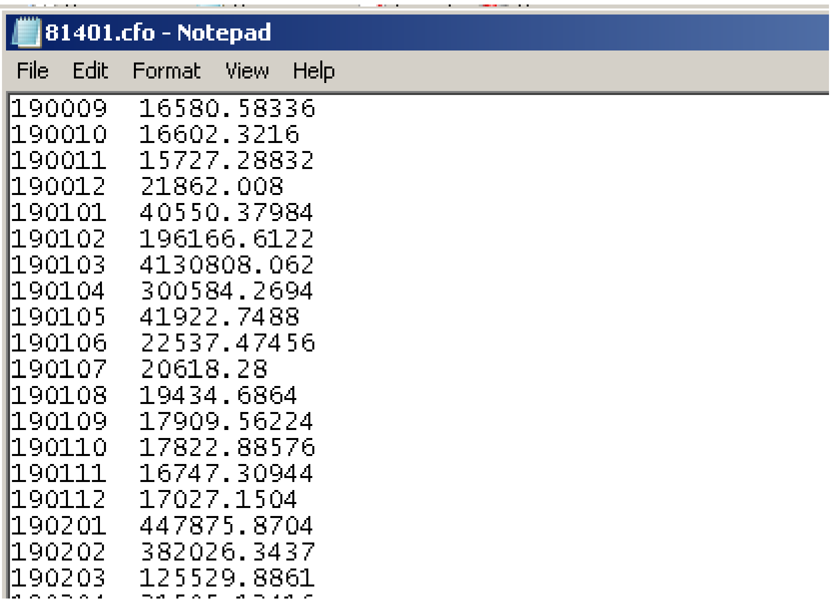
4. Save natural time series (predevelopment) as a comma delimited file (*.csv*). Change name to stream/station *name.nfo* (delete *.csv* and replace with *.nfo* in Windows Explorer) and place in 'Natural' folder. For example: gauging station number 81401 is saved as 81401.nfo. The left column is the monthly time step and the right column is the flow readings (ML/month). Do not include column headings.


81401.nfo - Notepad
File Edit Format View Help

190005	21824
190006	20144
190097	21147
190008	19280
190009	17977
190010	18065
190011	17127
190012	22929
190101	41536
190102	193784
190103	4123784
190104	303710
190105	44206
190106	24492
190107	22445
190108	21234
190109	19614
190110	19558
190111	18422
190112	18718
190201	449681
190202	385961
190203	127013

5. Save current (postdevelopment) time series as a comma delimited file (*.csv*). Change name to stream/station *name.cfo* (delete *.csv* and replace with *.cfo* in Windows Explorer) and place in 'Current' folder. For example: gauging station number 81401 is saved as 81401.cfo. The left column is the monthly time step and the right column is the flow readings (ML/month). Do not include column headings.

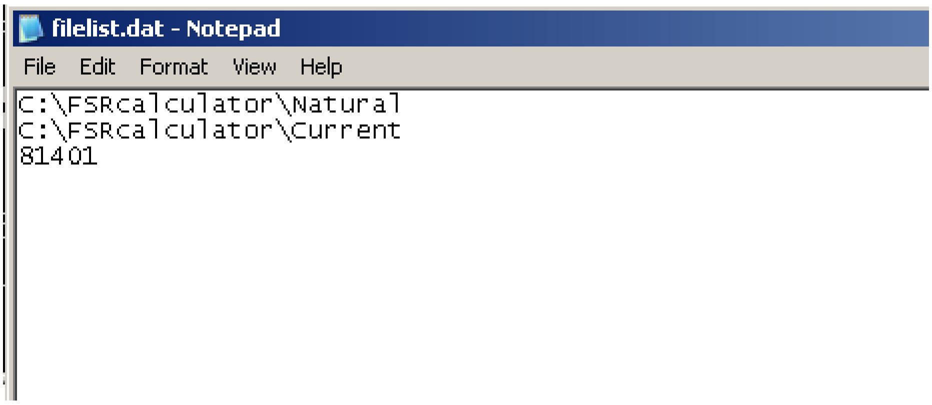
Make sure the *name.cfo* and *name.nfo* files have the same start and end dates. The calculator will not work if this is the case.


81401.cfo - Notepad

File Edit Format View Help

```
190009  16580.58336
190010  16602.3216
190011  15727.28832
190012  21862.008
190101  40550.37984
190102  196166.6122
190103  4130808.062
190104  300584.2694
190105  41922.7488
190106  22537.47456
190107  20618.28
190108  19434.6864
190109  17909.56224
190110  17822.88576
190111  16747.30944
190112  17027.1504
190201  447875.8704
190202  382026.3437
190203  125529.8861
```

6. Open C:/FSRCalculator/filelist.dat in Notepad and add in stream/station name (eg 81401). A number of stream names can be added and calculated at the one time.


filelist.dat - Notepad

File Edit Format View Help

```
C:\FSRcalculator\Natural
C:\FSRcalculator\Current
81401
```

7. Click NRETAS_FSR.exe, and follow prompts. 1st provide filelist.dat, 2nd an output file name (eg. Results01) and 3rd Select index calculation (option 2) (can choose other options if information relevant)

```
C:\FSRCalculator\nretas_fsr.exe

FSR Monthly Indices Program v 2.1
----------------------------------

Program configured for use by NRETAS 7 April 2009
Warning: users need to establish that the program output
     is consistent with their own independent checks and
     that the results are fit for intended purpose


This program requires an input file that lists:
1) full path of directory containing natural flows (on the 1st line)
2) full path of directory containing current flows (on the 2nd line)
3) names of all sites to be processed (on 3rd and subsequent lines)
   where each file consists of monthly data in the format:

YYYYMM    Flow

All data less than zero will be set to zero and assumed valid
All header lines commencing with ! will be ignored

Enter name of file containing directory and file list:
filelist.dat
No. of files to process:  1

Enter name of output file (*.out):
results01


Diagnostic dump file to include:
  1. No diagnostic information
  2. Index calculations
  3. Derived series and index calculations
  4. Extracted flows, derived series, and index calculations

Enter choice:
2_
```

Note: If there is something amiss with input files 'No. of files to process' will show 0.

8. Open output file (eg Results01) in Microsoft Excel.
Please see SKM 2004 for a full explanation of index calculations.

To apply the FSR in the wet/dry tropics look for:

- Q10w = wet season high flow
- Q90d and Q90g = averaged for dry and groundwater stress seasons and weighted by month = dry season low flow (for example calculation see below)
- PZDd and PZDg= averaged for dry and groundwater stress seasons and weighted by month = proportion of zero flow during the dry season
- SPm = seasonality
- CV = coefficient of variation

FSR Project Results Extraction
==============================

Date run: 8 December 2009 21:04

Variable definitions:
SiteID - Site identification
StrtDate- Start Date
EndDate - End Date
NumYr - Number of years of record
StrtLo - Start month of low flow water year (based on middle month of lowest 3 month season)
StrtHi - Start month of high flow water year (based on middle month of highest 3 month season)
CV - Ratio of CVs based on monthly data: min(CVNat,CVCurr)/max(CVNat,CVCurr)
Q90 - Variance-corrected 91.7 & 83.3th percentile index based on monthly data
Q10 - Variance-corrected 16.7 & 8.33th percentile index based on monthly data
PZD - Difference in proportion of zero monthly flows
SP - Seasonal periodicity (as used in SRA) based on monthly data
CVd - Ratio of CVs based on summer months: min(CVNat,CVCurr)/max(CVNat,CVCurr)
Q90d - Variance-corrected index based on lowest dry monthly flow
Q10d - Variance-corrected index based on highest dry monthly flow
PZDd - Difference in proportion of zero monthly flows over dry months
CVw - Ratio of CVs based on wet months: min(CVNat,CVCurr)/max(CVNat,CVCurr)
Q90w - Variance-corrected index based on lowest wet monthly flow
Q10w - Variance-corrected index based on highest wet monthly flow
PZDw - Difference in proportion of zero monthly flows over wet months
CVg - Ratio of CVs based on gw months: min(CVNat,CVCurr)/max(CVNat,CVCurr)
Q90g - Variance-corrected index based on lowest gw monthly flow
Q10g - Variance-corrected index based on highest gw monthly flow
PZDg - Difference in proportion of zero monthly flows over gw months
Annual - Overall annual hydrologic index (average of CV, Q90, Q10, PZD and SP)
Dry - Overall dry hydrologic index (average of CVd, Q90d, Q10d and PZDd)
Wet - Overall wet hydrologic index (average of CVw, Q90w, Q10w and PZDw)
GWstress- Overall g/w stress hydrologic index (average of CVg, Q90g, Q10g and PZDg)
AAPFD - AAPFD index using ISC rating (whole year)

Dry season indices based on flows in May to August only
Wet season indices based on flows in October to April only
Groundwater stress season indices based on flows in September to November only

SiteID	StrtDate	EndDate	NumYr	StrtLo	StrtHi	CV	Q90	Q10	PZD	SPm	CVd	Q90d	Q10d	PZDd	CVw	Q90w	Q10w	PZDw	CVg	Q90g	Q10g	PZDg	Annual	Dry
81401	01_1900	07_2007	107.58	Sep	Feb	0.983	0.6207	0.9818	0.9206	0.8785	0.4384	0.5868	0.8798	0.9198	0.9805	0.614	0.9898	0.9386	0.8321	0.5519	0.6884	0.8069	0.8769	0.706

Example: Dry season (May to November) low flow (7 months)
Dry season (May to August) = Q10d = 0.8798 (4 months or 0.57)
Groundwater stress season (Sept. to Nov.) = Q10g = 0.6884 (3 months or 0.43)

	Score	**Proportion**	**Score * prop**
Q90d	0.8798	0.57	0.5014
Q90g	0.6884	0.43	0.2960
Sum (Final Score)			0.7974

Trouble shooting

If difficulties persist re-copy FSR calculator from original source.

Appendix 4: Data sources of Daly River catchment dry season water quality data.

Table 13.4: Data sources for Daly River catchment dry season water quality data.

Data source	Project Title	Year
TRaCK	5.1 Edith River	2009
TRaCK	4.3 Milestone report	2008
NRETAS	Katherine River NHT flows	2006
NRETAS	NAPSWQ project	2005
NRETAS	AusRivAs MRHP	1995–2004
NRETAS	Vallisneria project	2001
NRETAS	EFI Algal project	2000
NRETAS	Historical Hydstra water quality data	1970–

Appendix 5: Percentiles and ranges of historical dry season water quality data in the Daly River catchment.

Table 13.5a: Percentile (95th) and ranges used in determining water quality attribute scoring bands (conductivity, turbidity, pH, soluble nutrients) for the Daly River catchment (80th, 20th, 5th also shown for interest).

River section	Percentiles					
Conductivity (µS/cm) percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	133	70.8	33.0	16.0	13.0	2.57–107
Katherine lower	75	596.3	563.6	330.7	290.7	290–600
Limestone	2	1317.1	1284.4	1110.0	1120.9	1110–1328
Flora	43	837.8	777.8	644.0	581.7	560–886
Daly upper to Douglas confluence	86	623.5	602.0	515.0	443.3	342–638
Douglas to Hayes Ck	20	536.1	524.4	371.8	282.9	261–576
Daly lower	34	659.1	589.2	492.2	459.2	453–679
Turbidity (NTU) percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	98	11.2	4.0	1.0	1.0	1.0–25.0
Katherine lower	42	2.9	2.8	2.0	1.8	1.7–3.2
Limestone *	2	15.3	13.3	5.1	3.0	2.35–16.0
Flora	12	6.7	4.6	1.3	0.9	0.86–7.0
Daly upper to Douglas confluence	53	4.1	3.0	1.0	1.2	1.0–7.0
Douglas to Hayes Ck	42	3.7	3.0	1.4	1.2	1.17–4.8
Daly lower	33	6.7	5.7	3.5	2.1	2.0–7.85
pH percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	151	7.58	6.91	6.16	5.70	4.46–8.40
Katherine lower	75	7.90	7.80	7.63	7.55	7.50–8.10
Limestone	2	8.27	8.24	8.28	8.08	8.07–8.28
Flora	43	8.07	7.76	7.44	7.21	7.10–8.24
Daly upper to Douglas confluence	87	8.19	8.01	7.52	7.29	6.76–8.29
Douglas to Hayes Ck	20	8.17	7.96	7.09	6.67	6.30–8.37
Daly lower	39	8.28	8.13	7.70	7.50	7.26–8.46
NO3 (µg/L) Percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	68	5	4	1	1	1–18
Katherine lower	53	369	329	64	1	1–381
Limestone	2	53	46	20	13	11–55
Flora	13	70	42	1	1	1–103
Daly upper to Douglas confluence	56	48	10	1	1	1–78
Douglas to Hayes Ck	18	157	97	55	79	12–270
Daly lower	23	11	8	2	1	1–15
FRP (µg/L) Percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	83	8	4	1	1	1–14
Katherine lower	44	5	5	4	4	3–13
Limestone	4	12	10	5	5	5–13
Flora	12	14	8	2	2	1–18
Daly upper to Douglas confluence	63	10	9	4	1	1–17
Douglas to Hayes Ck	19	12	10	1	2	1–13
Daly lower	34	17	13	7	2	1–19
where maximum and 95th percentile differ substantially						

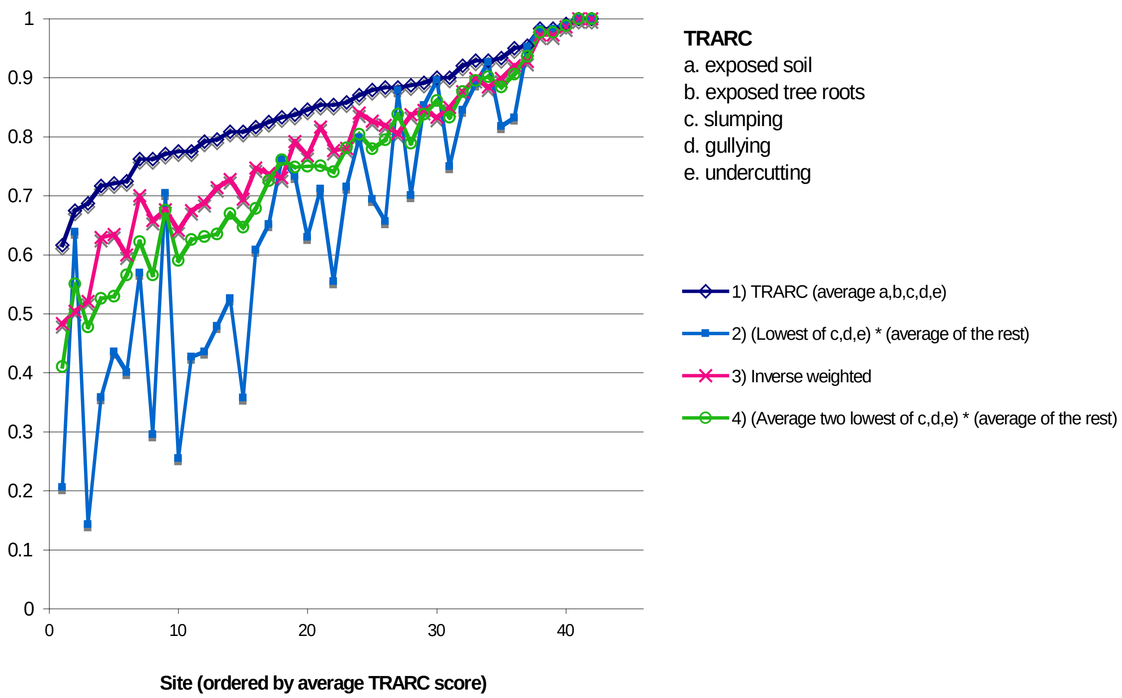
Table 13.5b Percentile (95th) and ranges used in determining water quality attribute scoring bands for total nutrients for the Daly River catchment (80th, 20th, 5th also shown for interest).

River section		Percentiles				
TN (µg/L) percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	33	226	150	56	43	40–300
Katherine lower	2	129	126	114	111	110–130
Limestone	4	249	173	100	100	100–270
Flora	11	163	118	60	37	30–170
Daly upper to Douglas confluence	41	139	90	31	9	6–181
Douglas to Hayes Ck	2	142	15	3	3	140–150
Daly lower	3	97	88	70	70	70–100
TP (µg/L) Percentiles	**n=**	**95**	**80**	**20**	**5**	**Range**
Sandstone upper reaches	98	31	14	5	3	1–51
Katherine lower	2	15	15	15	15	15–15
Limestone	4	15	15	7	6	5–15
Flora	15	22	10	4	2	1–25
Daly upper to Douglas confluence	69	20	8	3	2	1–20
Douglas to Hayes Ck	26	15	15	3	2	1–15
Daly lower	37	20	20	6	3	2–20

Appendix 6: Trialled integration of bank stability components

Scenario testing of options to integrate the TRARC erosion indicators into the FARWH bank stability theme are presented in Figure 122.6. Originally, TRARC indicators were simply averaged. However, the full range of scores between 0–1 was not possible because erosion features do not occur simultaneously. Also, the broad scoring bands used by TRARC meant that sites with extensive erosion scored highly in the FARWH bank stability subindex. Greater weighting is applied to slumping, gullying and undercutting as these erosion features have greater spatial impact and represent the majority of bank degradation in the wet/dry tropics. Various computations for weighting erosion metrics were explored, and the results are presented in Figure 122.6. Methods were rejected on the basis that they scored a site too ‘harshly’ (i.e. scores were worse than actual condition—Option 2) or too ‘favourably’ (i.e. scores are better than actual condition—Option 1). Options 3 and 4 produced similar results for this dataset. Option 4 was the preferred method as it applied greater weighting to slumping, gullying and undercutting as these erosion features have greater spatial impact and represent the majority of bank degradation in the wet/dry tropics.

Figure 122.6: Options considered for integration of TRARC erosion scores (a,b,c,d,e) into the FARWH bank stability subindex. Data from the Daly River catchment 2009. Sites ordered from lowest to highest average TRARC-erosion scores. Option 1 is standard TRARC approach used in the desktop trials of FARWH (Darwin and Ord catchments); Option 2 gives higher weighting to c, d or e; Option 3 gives sequential weighting from lowest to highest scores; and Option 4, the preferred method, gives higher weighting to two of c, d or e.



Appendix 7: Fish modelling in the Daly River catchment.

Introduction

Fish have been documented to respond to a wide range of anthropogenic impacts associated with water infrastructure developments, agricultural pesticides, nutrient enrichment, acid-sulphate runoff, mining activities, forestry operations and river channellisation (for reviews, see Kennard et al. 2001 and Pusey and Kennard 2009). Fish have also been suggested to be sensitive to impacts associated with agricultural activities (e.g. cropping and cattle grazing), as well as urban and industrial developments. These potential sources of disturbance can function singularly or interact to directly and/or indirectly affect the availability and suitability of resources required for refuge, feeding, spawning and recruitment, or cause lethal and/or sublethal effects on fish health (Figure 1). Impacts on fish may therefore be manifest on individuals, populations and/or assemblages.

The impacts of land-use practices on fish are complex but can affect water quality, habitat suitability and resource availability through elevated inputs of sediments, toxicants (e.g. agricultural pesticides and herbicides, industrial wastes) and nutrients (e.g. fertilisers, sewage effluents) (Figure 1). Terrestrial and riparian vegetation may become degraded due to direct removal and replacement by crops or pasture, invasion by exotic species and/or livestock trampling. Livestock can also lead to aquatic habitat degradation by direct trampling and increased delivery of nutrients and organic matter by faecal deposition. Degraded riparian zones can result in decreased interception rates of sediments, toxicants and nutrients and result in bank slumping and associated stream channel modifications. Riparian degradation can affect fish due to increased light penetration causing changes in water quality (increased temperature and dissolved oxygen fluctuations beyond tolerable levels), changes in primary (e.g. algal blooms and aquatic weed infestations) and secondary production, and reduced inputs of allochthonous organic matter as habitat and/or food (e.g. leaf litter, woody debris, terrestrial organisms). Increased sediment delivery to the stream and associated increased turbidity has been suggested to impact on fish by altering food availability (e.g. benthic invertebrates and algae), reducing foraging efficiency, altering fish behavioural patterns, affecting habitat suitability (e.g. smothering of coarse gravel beds) for spawning, foraging and refuge, increasing physiological stress, increasing egg mortality and reducing rates of larval development and survival.

The documented responses of fish to a diverse range of anthropogenic disturbances suggest that fish may be sensitive indicators of the net effect of human impacts on aquatic ecosystems. Fish also provide an easily interpretable endpoint of environmental degradation (Hendricks et al. 1980) and can be used as a justification for remedial action, given their ecological, social and economic importance.

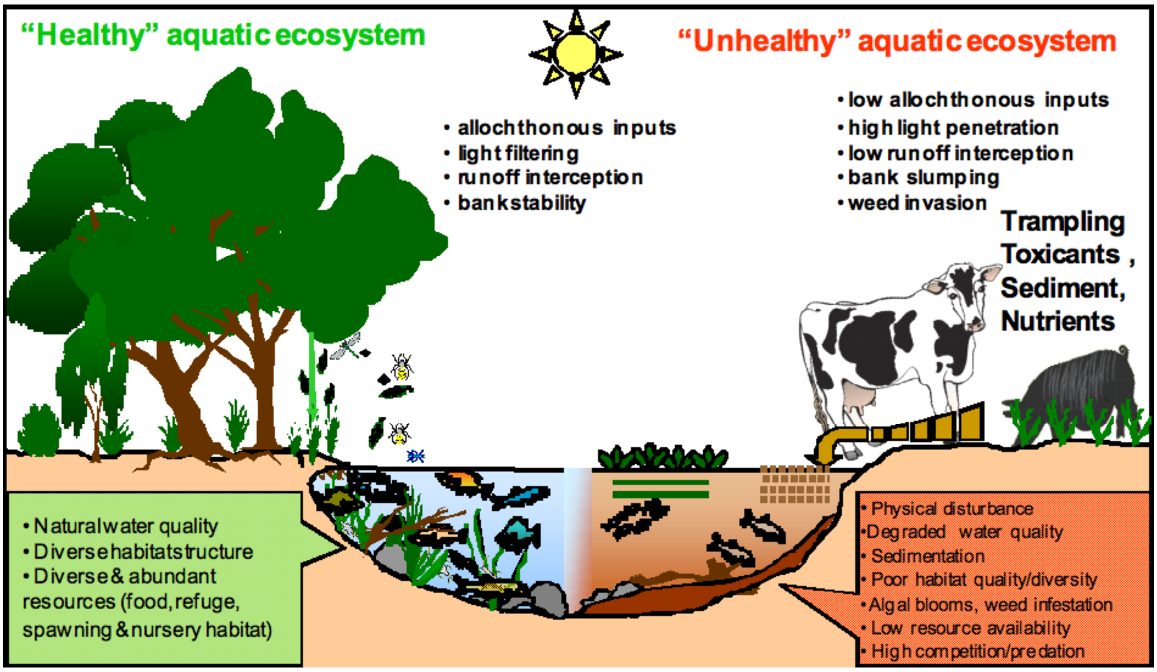


Figure 1: Conceptual model of predicted changes in physical and biological characteristics of aquatic ecosystems that potentially affect fish assemblages with increasing levels of disturbance due to human land-use practices (particularly impacts associated with cattle grazing and associated local riparian, instream habitat and water quality degradation). Healthy aquatic ecosystems would be expected to contain a diverse array of habitats and resources for fish refuge, feeding, spawning and larval development. Fish assemblages would be characterised by species from a range of habitats and trophic guilds (varying spatially and temporally with local and landscape scale environmental features) and a diverse range of size/age classes. With increasing levels of anthropogenic disturbance, a decrease in the availability and/or suitability of habitat and other resources may be expected, leading to increased potential for biotic interactions and intolerable conditions for sensitive fish species. Fewer native species would be expected and the fish assemblage may be characterised by low structural and functional diversity (Figure modified from Kennard et al. 2001)

There is currently no biological assessment program for Australia's tropical rivers that uses standardised indicators of river health based on attributes of freshwater fish communities and none of the key requirements of a fish-based monitoring program (see Kennard 2005) have been systematically evaluated in the region. For example, there is currently no standardised sampling program for fish communities undertaken throughout northern Australia's freshwaters. Although several fish-sampling datasets have been collected by various government agencies, universities and private consultants as part of monitoring programs and research projects, each of these fish-sampling programs was undertaken with varying objectives. Thus, sampling methods vary substantially, as does the spatial and temporal scale of collecting and the types of fish data collected. Assessment of the natural ranges in spatial and temporal variation of fish communities and the drivers of this variation has received little attention for tropical rivers. In addition, the ability to accurately define the reference condition for biological attributes expected in the absence of anthropogenic stress using predictive modelling approaches has not yet been undertaken in the region.

These issues present considerable challenges to the development of standardised indicators of river health based on attributes of freshwater fish communities for tropical rivers. Nevertheless, recent quantitative sampling of fish communities at numerous sites throughout the Daly River (undertaken through the TRaCK research program) presents an opportunity to trial the development of a fish-based river health assessment program for Australia's tropical rivers.

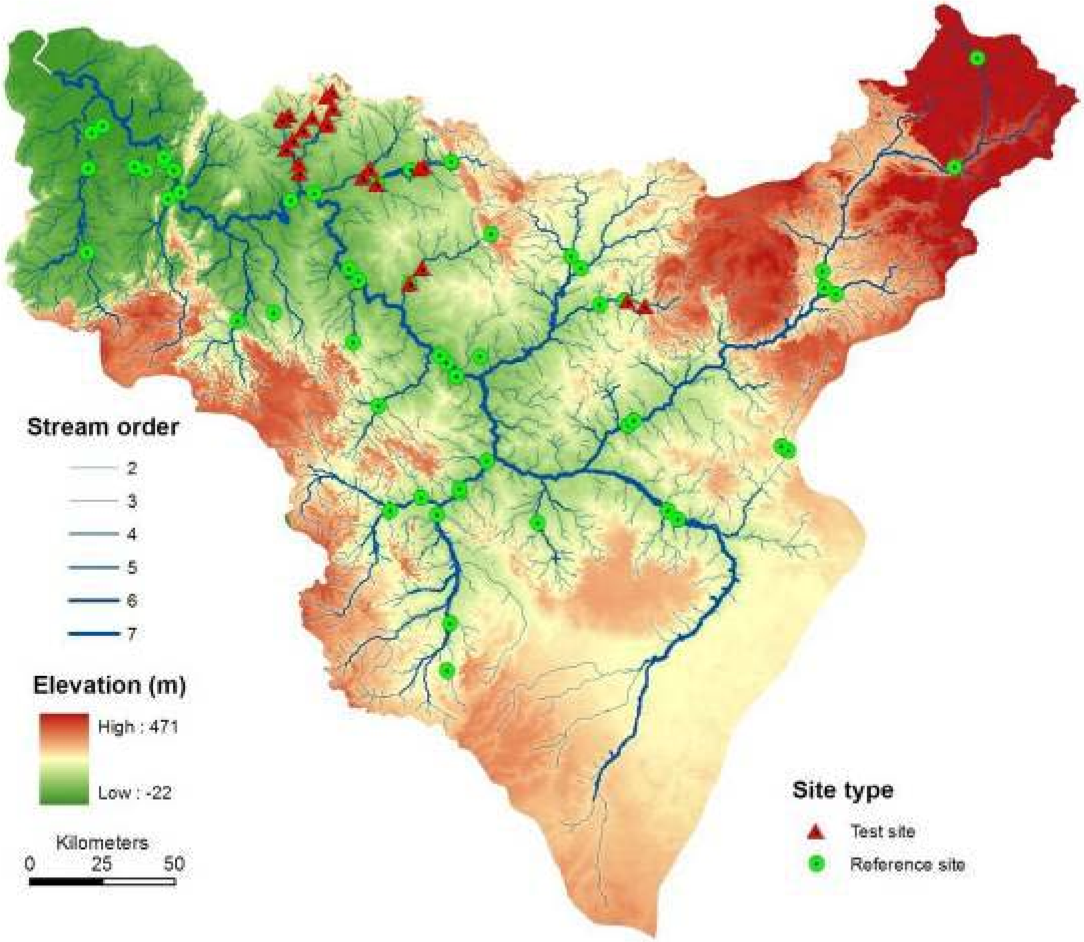
In the present study we evaluate alternative approaches for the use of summary attributes of fish assemblage structure and function as indicators of aquatic ecosystem health. Freshwater fish were surveyed at a large number of sites subject to varying intensities of disturbance due primarily to cattle grazing, feral animal activity and associated local riparian, instream habitat and water quality degradation. These are hereafter referred to as test sites. Biological condition of the test sites was assessed with reference to the expected natural state (the reference condition approach, Reynoldson et al. 1997), such that natural variation in fish assemblages along natural environmental gradients could be separated from disturbance induced change. The biological attributes of the reference condition were derived from predictive models based on relationships of environmental variables with the structural and functional characteristics of fish assemblages. These included predictive models of fish assemblage composition (presence/absence of species) assemblage structure (relative abundance of species) and ecological trait composition (based on fish species morphology, habitat use, reproduction, movement and trophic requirements). These latter characteristics may provide a potentially useful diagnostic role in ecosystem health assessment. Predictive models were developed and validated using a set of minimally disturbed reference sites located throughout the Daly River. Predictive models that could be successfully calibrated were used to predict the expected fish assemblage characteristics at the test sites. Deviations from model predictions at the test sites were then related to a suite of variables describing the source and intensity of disturbance at the test sites using a post-hoc correlative approach.

Methods

Study area

A sampling location is defined for the purpose of this study as being a section of river/stream or billabong that was broadly similar in terms of fluvial geomorphology, hydrology etc. In practice, sampling locations were usually less than 1 km in length. As part of a prior environmental flows study (undertaken through the TRaCK program), dry season sampling of freshwater fish communities was conducted at 55 locations throughout the Daly River catchment during 2006–08 (Figure 1). These sites were minimally disturbed by anthropogenic activity (hereafter termed reference sites) and encompassed as much of the natural biological and environmental variation as possible in the catchment within the scope of the field sampling program. Twenty-four sites were selected to test the predictive models and to examine whether differences in observed versus predicted fish assemblages was related to known gradients in anthropogenic disturbance (particularly impacts associated with cattle grazing, feral animal activity and associated local riparian, instream habitat and water quality degradation). These test sites ranged from minimally disturbed to highly impacted and were sampled in the dry season of 2009. The range of variation in environmental conditions at test sites was well within the range of variation at reference sites (Table 1) and they were hence deemed comparable for the purposes of predictive model development and application.

Figure 1: Location of reference and test sites in the Daly River catchment, Northern Territory.



Fish sampling methods

Full details on the sampling methodology and evaluation of the accuracy, precision and efficiency of the sampling protocol are presented in Kennard et al. (2009). Within each selected sampling site, fish assemblages were sampled by electrofishing (boat and/or backpack) at multiple discrete locations within each site. These samples are hereafter termed electrofishing 'shots', with each shot fixed at five minutes duration (elapsed time). At least 10 electrofishing shots were usually undertaken at each site as this level of effort provided highly accurate and precise estimates of local fish assemblage attributes. Replicate measures of a range of hydraulic and microhabitat parameters were taken for each shot. Fish collected from each electrofishing shot were identified to species level, counted and returned to the approximate point of capture. Fish data collected using other supplementary sampling methods (e.g. netting, angling) is not considered in this report. From this data we estimated species composition (the presence or absence of species) and species relative abundance (the percentage of the total number of individuals) at each sampling site.

Environmental predictor variables

Ten ecologically relevant landscape-scale environmental variables were selected from a larger number of candidate variables for use in the predictive models of fish assemblage attributes (Table 1). Principal components analysis and Spearman's correlations among variables were used to identify and remove highly correlated variables. Spearman's correlation coefficients among the final set of predictor variables usually ranged between 0.5 and +0.5. Environmental predictor variables described hydrology (mean and coefficient of variation in annual discharge, estimated using a catchment water balance model), temperature (mean annual minimum temperature), river basin topography (distance to river mouth, slope, valley confinement (indicative of the depositional environment and the potential for stream aquifer connectivity) and catchment storage (relative proportion of depositional/floodplain areas in the catchment), substrate hydrogeological properties, which can shape ecologically important properties of the stream hydrograph (sedimentary rocks and soil hydraulic conductivity) and vegetation (natural tree cover). A detailed description of all environmental variables and their methods of derivation are described in Stein et al. (2009). Several local-scale environmental variables describing the habitat characteristics of each reference site were also used to develop predictive models. These included mean water-column depth, mean water velocity and the mean aerial proportion of aquatic vegetation (macrophytes and algae), organic matter (woody debris and leaf litter) and bankside structures (undercut banks and root masses).

Table 1: Range and median values of environmental predictor variables at reference and test sites. See Stein et al.. (2009) for further background on environmental variables and their methods of derivation.

Variable	Description	Site type	Minimum	Median	Maximum
Mean annual discharge	Mean annual discharge (GL/year x 10^3)	Reference	0.6	229.5	9306.7
		Test	3.0	53.2	379.5
CV annual discharge	CV annual discharge	Reference	0.58	0.79	1.41
		Test	0.60	0.65	0.87
Sedimentary rocks	Catchment siliclastic/undifferentiated sedimentary rocks (%)	Reference	0.0	35.3	89.8
		Test	1.5	31.3	83.5
Hydraulic conductivity	Catchment average saturated hydraulic conductivity (mm/h)	Reference	30	205	300
		Test	100	232	300
Tree cover	Catchment tree cover (%)	Reference	7	72	100
		Test	16	74	97
Temperature	Stream and environs mean minimum annual temperature (oC)	Reference	11.4	12.7	14.1
		Test	12.5	13.4	13.5
Valley confinement	Percentage of stream reach grid cells and their immediate neighbours that are not valley bottoms as defined by mrVBF and mrRTF indices)	Reference	0	21	100
		Test	0	9	100
Slope	Stream reach slope	Reference	0.00	0.08	1.99
		Test	0.01	0.20	0.62
Catchment storage	Relative proportion of depositional areas (valley bottoms) in the catchment	Reference	0	17	75
		Test	3	21	34
Distance to river mouth	(Km)	Reference	50	352	762
		Test	207	240	452

Fish assemblage indicators and rationale

A comparison of fish species composition (presence/absence) predicted to occur on the basis of environmental features with the species actually present at a site can provide an indication of the health of the fish community (Kennard et al. 2006 and references therein). The composition of native species in degraded stream reaches is likely to differ from that expected in undisturbed streams of similar type. The ratio of the observed number of species (O) to the expected number of species (E) can be used as a summary of ecosystem health on the basis of native fish species composition (indicator hereafter termed fish assemblage O/E).

Deviations in the relative abundances of individual species from reference predictions can also provide an indication of the health of the fish assemblage at a test site. Given knowledge of their ecological and life history requirements, and their environmental tolerances, they can also be used to pinpoint the source of the disturbance and allow suitable rehabilitation to be implemented.

A more direct measure of fish responses to anthropogenic disturbance is to assess the functional characteristics of fish assemblages based on the morphology of the habitat use of fish species, reproduction, movement and trophic requirements (e.g. see Karr and Chu 1999 and references therein). For example, the number of species in specific habitat guilds (pelagic and benthic pool species and riffle species) has been used as a direct indicator of instream habitat degradation (e.g. due to sedimentation, de-snagging, weed infestation and excessive algal growth) (Figure 1). It is predicted that the number of species in these guilds will decline with increasing disturbance to instream habitat structure. The trophic composition of fish assemblages can also be used to indicate changes in food resource availability and riparian/aquatic ecological processes. It is hypothesised that deterioration in riparian and instream habitat and water quality is likely to impact on aquatic invertebrate production and reduces the contribution of terrestrial arthropods to the stream environment (Figure 1). This is expected to result in a decline in the relative abundance of fish species that are invertivores and/or piscivores. Under conditions of eutrophication and increased algal production due to riparian vegetation removal and nutrient enrichment, it may be expected that the proportion of individuals that are herbivores/detritivores may increase. The relative abundance of omnivorous species that are able to exploit a wide range of food resources may also be expected to increase in disturbed conditions.

Using published and unpublished data and expert opinion, we collated data for 16 ecological and life history attributes that could be justified on the basis of our current state of knowledge and information available for the majority of species (Table 2). Functional trait composition at each site was calculated as the relative proportion of fish species present at each site belonging to each trait state within each of the 16 trait categories (see Olden and Kennard 2010 for further details).

Table 2: Candidate ecological and life history traits quantified for freshwater fishes of the Daly River for use as diagnostic indicators of river health. The relative proportion (%) of the 39 fish species within each trait state is shown for each trait category.

Trait	%	Trait	%
Morphology		**Reproduction**	
Maximum length (cm)		*Longevity (months)*	
<11.75	25.6	<36	30.8
11.75–33.00	28.2	37–60	51.3
33.01–51.25	23.1	>60	17.9
>51.25	23.1	*Spawning frequency*	
Shape factor (TL[1]/body depth)		Single	46.2
<3.51	25.6	Batch	53.8
3.52–4.33	28.2	*Relative length at maturation (cm/max TL)*	
4.34–5.47	23.1	<0.35	25.6
>5.47	23.1	0.36–0.45	30.8
Swim factor (caudal peduncle depth/body depth)		0.46–0.50	23.1
<0.35	25.6	>0.5	20.5
0.36–0.38	17.9	*Total seasonal fecundity*	
0.39–0.44	33.3	<650	23.1
>0.44	23.1	651–8750	25.6
Eye size (eye diameter/TL)		8750–81250	28.2
<0.036	30.8	>81250	23.1
0.037–0.045	20.5	*Egg size (mm)*	
0.046–0.067	20.5	<0.575	25.6
>0.067	28.2	0.576–1.04	25.6
Maxilla size (maxilla length/TL)		1.05–1.5	28.2
<0.041	25.6	>1.5	20.5
0.042–0.055	23.1	*Parental care[2]*	
0.056–0.095	25.6	0	17.9
>0.095	25.6	1	53.8
Habitat preference		2	17.9
Juvenile meso-habitat use		3	10.3
Lentic & floodplain	10.3	**Movement classification**	
Shallow pools & runs	20.5	Sedentary	46.2
Deep pools & runs	23.1	Potamodromous	38.5
Shallow riffles & runs	17.9	Amphidromous	2.6
Shallow fast riffles	28.2	Catadromous	12.8
Adult meso-habitat use		**Trophic guild**	
Lentic & floodplain	10.3	Herbivore-detritivore (>25% plant matter)	12.8
Shallow pools & runs	20.5		
Deep pools & runs	35.9	Omnivore (5–25% plant matter)	23.1
Shallow riffles & runs	12.8		
Shallow fast riffles	20.5	Invertivore	38.5
Vertical position		Invertivore-piscivore (>10% Fish)	25.6
Benthic	33.3		
Non-benthic	66.7		

[1] TL refers to total body length.
[2] Parental care follows Winemiller (1989) and was quantified as the Σxi for i =1 to 3; x1 = 0 if no special placement of zygotes, x1 = 1 if special placement of zygotes, x1 = 2 if both zygotes and larvae maintained in nest; x2 = 0 if no parental protection of zygotes or larvae, x2 = 1 if brief period of protection by one sex (< 1 month), x2 = 2 if long period of protection by one sex (> 1 month) or brief care by both sexes, x2 = 4 or lengthy protection by both sexes (> 1 month); x3 = 0 if no nutritional contribution to larvae, x3 = 2 if brief period of nutritional contribution to larvae (< 1 month), x3 = 4 if long period of nutritional contribution to larvae (1-2 months), x2 = 8 if extremely long period of nutritional contribution to larvae (> 2 months).

Statistical analyses

Predictive model development

The presence or absence of species, relative abundance and functional trait composition were modelled as a function of the environmental predictor variables using multiresponse artificial neural networks (see Olden 2003; Olden et al. 2006a). In addition to the flexibility of neural networks to model multiple response variables, they are capable of modelling nonlinear associations with a variety of data types, require no specific assumptions concerning the distributional characteristics of the independent variables, and can accommodate interactions among predictor variables without any a priori specification (Bishop 1995). Neural networks have been shown to exhibit substantially higher predictive power (based on empirical and simulated data) when modelling nonlinear relationships compared to logistic regression, linear discriminant analysis or classification trees (Olden and Jackson 2002).

We used feed-forward neural networks trained by the backpropagation algorithm to model spatial and temporal variation in three response variables: the presence or absence of species, relative abundance and relative biomass. The architecture of these networks consisted of a single input, hidden and output layer. The input layer contained one neuron for each of the environmental variables. The number of neurons in the single hidden layer was chosen to minimise the trade-off between network bias and variance by comparing the performances of different cross-validated networks, with 2 to 50 hidden neurons (increasing by increments of 2), and choosing the number that produced the greatest external network performance. The output layer contained one neuron for each response variable being modelled, representing either the probability of the presence or absence of species, the relative abundance of species or the frequency of occurrence of each trait state (note predictive models were developed for separately for each trait group, i.e. morphology, habitat use, reproduction, movement and trophic guild).

Model training involved the cross-entropy error function for binary variables (the presence or absence of species) and the sums-of-squared error function for continuous variables (the relative abundance of species and functional trait composition). Learning rate (η) and momentum (α) parameters (varying as a function of network error) were included during network training to ensure a high probability of global network convergence and a maximum of 1000 iterations for the backpropagation algorithm to determine the optimal axon weights. We refer the reader to Olden (2003) and Olden et al. (2006a) for more methodological details. The contributions of the environmental variables in the neural networks were quantified by calculating the product of the input-hidden and hidden-output connection weights between each input neuron and output neuron and then summing the products across all hidden neurons. This approach is deemed the most appropriate as it has been shown to outperform other techniques for quantifying variable contributions in neural networks (Olden et al. 2004). All neural network analyses were conducted using computer macros written in the MatLab® (The MathWorks, Natick, Massachusetts, USA) programming language.

Predictive model validation and performance

Cross validation was used to generate model predictions and assess classification performance of the neural networks based on the reference site data. This validation method excludes one observation, constructs the model with the remaining n–1 observations, predicts the response of the excluded observation using this model, and repeats the procedure n times. Model performance for the presence or absence of species was assessed by calculating overall classification performance (percentage of sites where the model correctly predicts the presence or absence) of species, sensitivity (percentage of the sites where the presence of species was correctly predicted) specificity (percentage of the sites where the absence of species was correctly predicted). The choice of probability threshold above which each species is predicted to occur is often arbitrarily set to 0.5, but this does not necessarily preserve the observed prevalence or result in the highest prediction accuracy, especially for data sets with very high or very low observed prevalence (Freeman and Moisen 2008). There are many potential criteria which can be used to determine the optimum threshold, but the choice ultimately depends on the intended use of the predictive model. Nevertheless, comparative studies (see Freeman and Moisen 2008 for review) have shown that the choice of criteria can substantially affect model prediction error. Our objective was to derive unbiased estimates of the prevalence of species (i.e. minimise false presences and absences), so we used a threshold in which the predicted prevalence equalled the observed prevalence (as recommended by Freeman and Moisan 2008). We evaluated model performance, using the area under the receiver-operating characteristic curve (AUC) (see Fielding and Bell 1997) based on the *n*-fold cross-validated model predictions. An AUC>0.6 is usually defined as acceptable model performance (Fielding and Bell 1997).

The ratio of the observed number of species (O) to the expected number of species (E) gives an indication of the degree of fidelity between the fish assemblage observed at a test site with that expected and, theoretically, is an indication of the predictive capability of the model (the closer to 1.0, the better the match between observed and expected assemblage; see Kennard et al. 2006 and references therein). The expected number of species at each test site was equal to the sum of the individual probabilities of all the species predicted to occur (i.e. those species with a predicted probability of occurrence greater than the species-specific threshold). We evaluated relationships between the observed number of species at reference sites and the number of species predicted and expected to occur using bi-plots and simple linear regression models. We also evaluated whether the total number of species at a site biased model predictions by regressing species richness against O/E scores of reference sites.

Model performance for the relative abundance of species and functional trait composition was assessed using Pearson's product-moment correlation coefficient (r) (a measure of prediction accuracy).

For all response variables, we evaluated the effects of using different predictor variable sets on model performance (i.e. landscape-scale variables only and landscape scale plus local-scale variables). Predictive models developed using only landscape-scale predictor variables would be preferable in the context of this study as local scale habitat variables are more likely to be affected by anthropogenic disturbance, and hence may bias model predictions at test sites.

Relationships of fish assemblage indicators with anthropogenic disturbance

For the subset of fish species response variables that could be accurately predicted at test sites (see Results), we used the following procedures to evaluate their relationships with indicators of anthropogenic disturbance at test sites and hence gauge their potential as indicators of ecosystem health (see Chapter 11, 'Testing of indicators to disturbance')

Results

Characteristics of the fish fauna at reference and test sites

Quantitative sampling of the fish fauna from the Daly River resulted in the collection of 22 214 individuals from 39 species at the 55 reference sites and 6382 fish from 24 species from the 24 test sites (Figure 2a & b). The most widespread species collected at the reference sites were *Mel australis, Lei unicolor, Oxy selheimi, Mog mogurda* and *Glo aprion*, occurring at over 70% of all sites surveyed (Figure 2a). *Lei unicolor, Mel australis, Mog mogurda* were also among the most widespread species among test sites, but *Hep fuliginosus* and *Cra stramineus* were relatively more widespread at test sites than at reference sites. *Mel australis, Lei unicolor, Amb sp*., *Cra stramineus* and *Mog mogurda* were the most abundant species at reference sites, collectively forming 62% of the total sampled (Figure 2b). *Mel australis, Lei unicolor, Cra stramineus, Mog mogurda* and *Hep fuliginosus* were the most commonly sampled species at test sites, collectively forming 89% of the total.

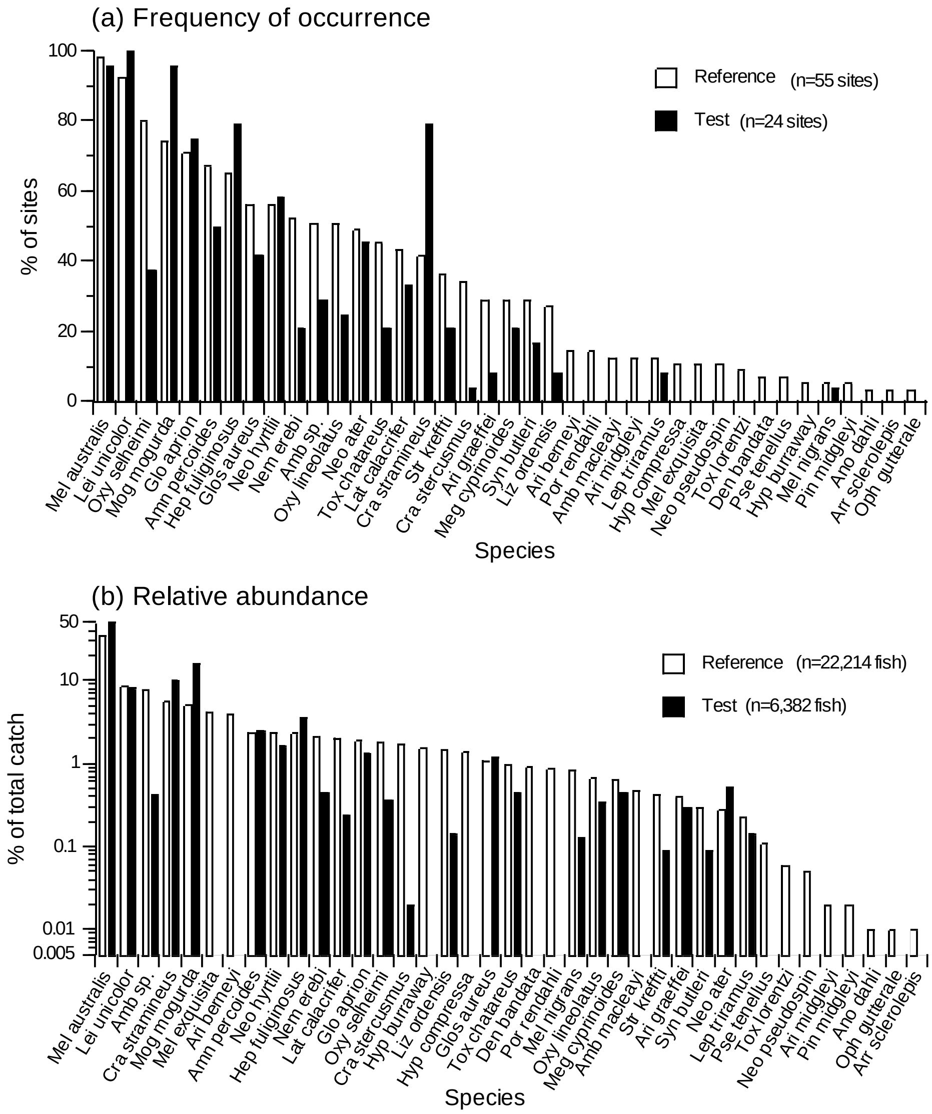


Figure 2: Biological characteristics of the reference sites (open bars) and test sites (closed bars) showing a) the frequency of occurrence and b) the relative abundance of fish species collected. The total number of reference and test sites sampled and total number of fish collected at each site type is shown in parentheses.

Development and validation of predictive models

The multiresponse neural network predictive models exhibited high success in predicting the presence of individual species or their absence in the Daly River reference sites, irrespective of the predictor variable sets used in model development. The mean correct classification rate or the presence or absence of species was >80%. Using the 10 landscape-scale variables alone and the addition of five local-scale predictor variables contributed little to the predictive success (Figure 3a).

The predictive models of the relative abundance of species in the Daly River reference sites were moderately accurate. (Figure 3b) Correlation coefficients (Pearson's r values) between predicted and observed values for each species averaged 0.48 when modelled, using landscape scale environmental variables. Predictions were slightly better (mean r = 0.60) when using landscape plus local-scale variables as predictors of relative abundances of species.

The predictive models of functional trait composition at Daly River reference sites were generally poor (Figure 3c). Mean correlation coefficients (Pearson's r values) between predicted and observed values for each trait category were always less than 0.40. The use of local-scale environmental variables did not substantially improve predictive model performance (data not shown).

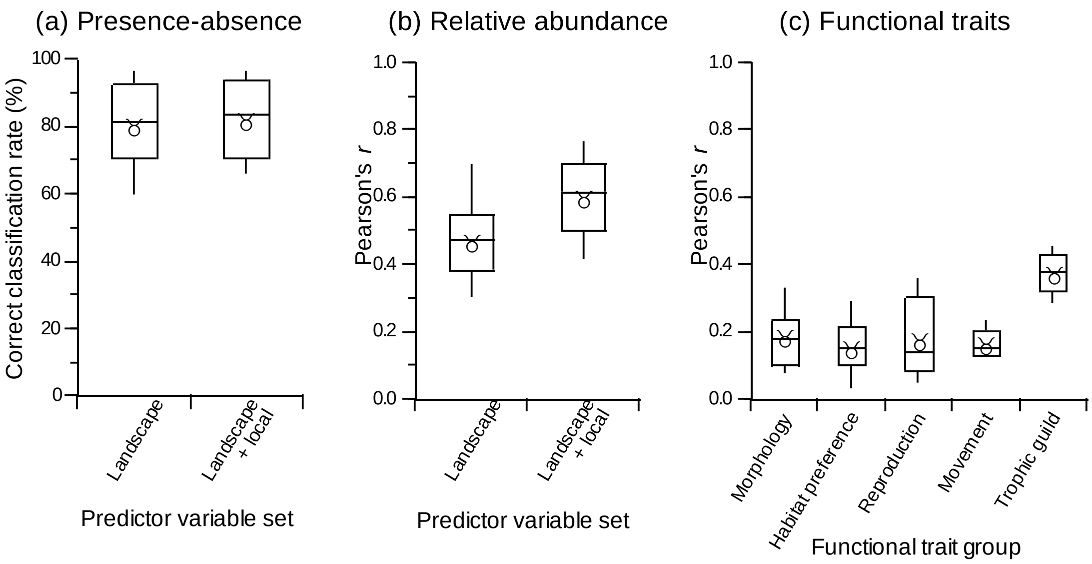
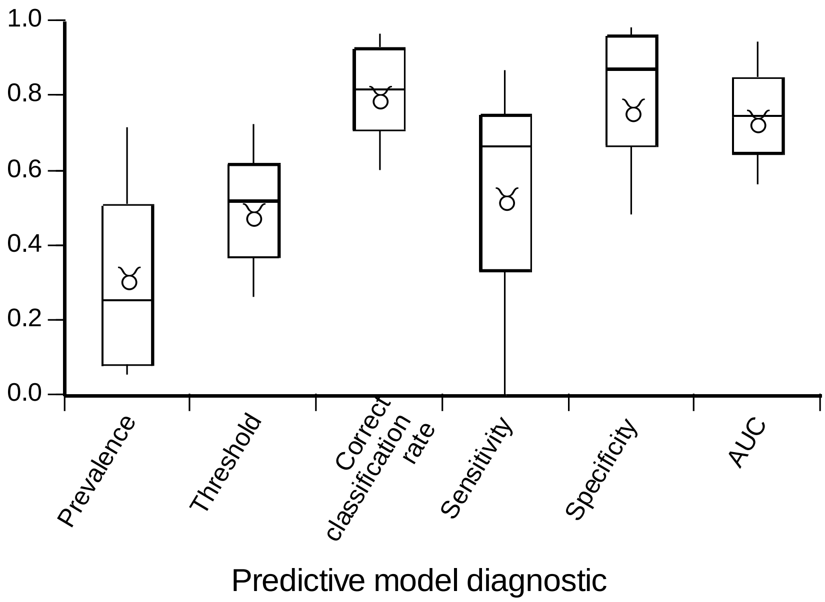


Figure 3: Box plots show variation across the 39 species in predictive model performance for predicting (a) the presence or absence of species, (b) the relative abundance of species and (c) functional trait composition. Model performance is quantified using correct classification rate for the presence or absence of individual species and Pearson's *r* for the relative abundance of species and functional trait composition, respectively. The effect on model performance of using different variable sets for predicting the presence or absence of species and the relative abundance of species is also presented.

Given the poor to moderate performance of models developed to predict spatial variation in the relative abundance of species, and functional trait composition, it would not be prudent to attempt to predict these fish assemblage attributes at the test sites. In contrast, the high predictive accuracy of the models developed to predict the presence or absence of species implies that these models could be reliably used to predict species composition at test sites. We therefore provide further details on the predictive performance of these models, focusing on the model developed, using landscape-scale environmental predictor data.

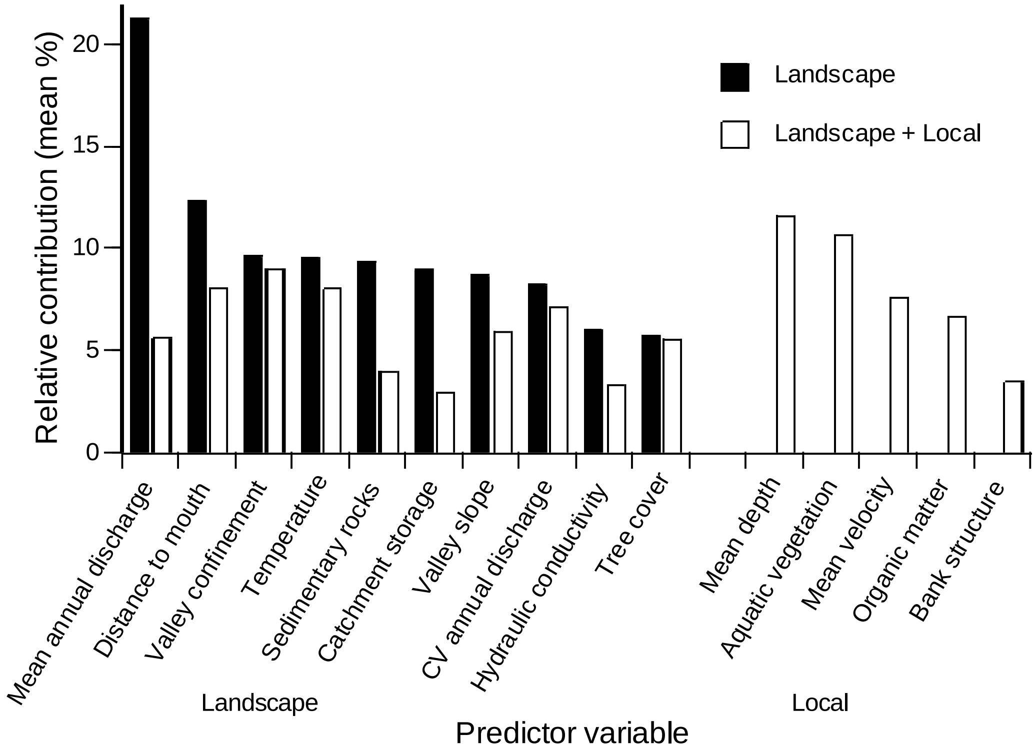
The 39 fish species used to develop the predictive model of the presence or absence of species ranged in prevalence from 0.02 to 0.98 (mean = 0.32) across the 55 reference sites (Figure 4; see also Figure 2a) and probability thresholds above which each species was predicted to occur ranged from 0.29 to 0.92 (mean = 0.49) (Figure 4). As reported earlier, the correct classification of the presence or absence of species was generally high (mean = 0.81) and all but five species had correct classification rates exceeding 0.7 (minimum = 0.56). Overall, the model was better able to correctly predict the absence of species than their presence (mean specificity = 0.77 and mean sensitivity = 0.55); an expected result given the low frequency of occurrence of many species in the dataset. The model had difficulty predicting the presence of rare species (i.e. low sensitivity) and the absence of some widespread species (low specificity). Nevertheless, generally high AUC values (mean = 0.75) indicate very good overall predictive performance (Figure 4).

Figure 4: Diagnostic features of the predictive model of the presence or absence of species, using landscape scale predictor variables. Box plots show variation across the 39 fish species in terms of: species prevalence, threshold values, correct classification rate, model sensitivity, specificity, and area under the curve (AUC) values.



Mean annual discharge and distance to the river mouth were the two most important landscape-scale environmental predictors of species occurrences in the Daly River reference sites (mean relative contribution = 23% and 12%, respectively, Figure 5). The remaining eight landscape-scale predictor variables individually contributed less than 10% to overall model predictions. Local-scale environmental variables were often more important predictors of variation in the presence or absence of fish species when used together with landscape-scale variables (in particular mean water depth, aquatic vegetation and mean water velocity, Figure 5).

Figure 5: Relative contributions of environmental variables for predicting the presence or absence of species (averaged across the 39 fish species) using landscape scale variables or landscape plus local scale variables in each model.



The predictive model based on landscape variables alone provided unbiased and precise estimates of species composition at reference sites. Strong relationships existed between the observed number of species at reference sites and the number of species predicted and expected to occur (R2 = 0.77 for both relationships; Figure 6a,b). The number of species present at a site did not affect model performance and predictive accuracy as there was no relationship between the number of species present at a site and observed/expected (O/E) ratios (R2 = 0.09; Figure 6c). O/E ratios for reference sites were generally close to unity with a relatively low intersite variation (mean O/E = 1.01 ± 0.13 S.D.; Figure 6d, Table 3), further implying that the model provided accurate and precise estimates of fish assemblage composition. Consequently, this model was considered valid for predicting species composition at the 24 test sites.

Figure 6: Relationships between the observed number of species reference sites and (a) the predicted number of species (i.e. those species predicted to occur at > the presence or absence threshold), (b) the expected number of species (sum of the individual species probabilities' of occurrence > the presence or absence threshold), and (c) observed/expected (O/E) ratios. Cumulative frequency distributions of O/E ratios for reference and test sites is shown in (d).

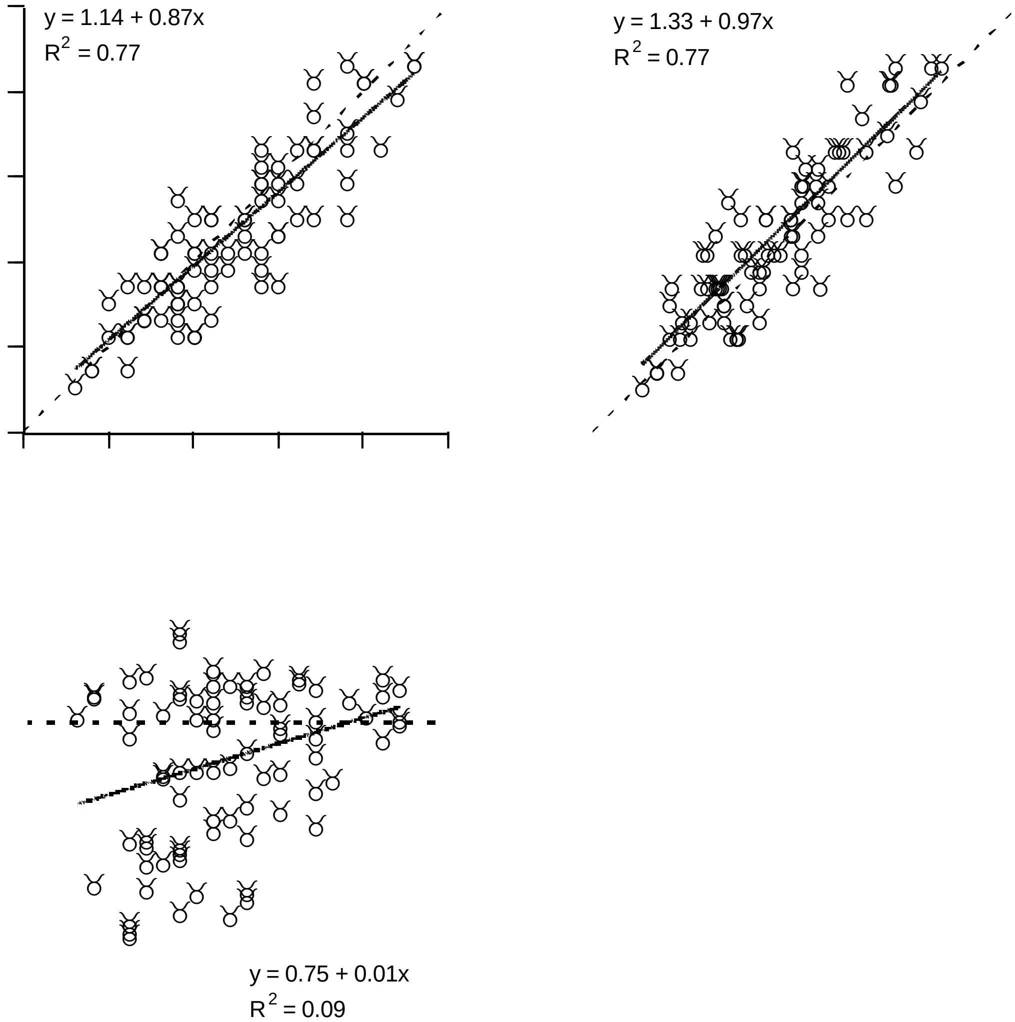


Table 3: Range and mean (± S.D.) values of the number of species predicted (P), expected (E) and observed (O) at reference and test sites. Also shown are the range and mean (± S.D.) O/E) ratios for reference and test sites and the width of the reference band (90th–10th percentile of all reference site O/E scores) is shown in parentheses.

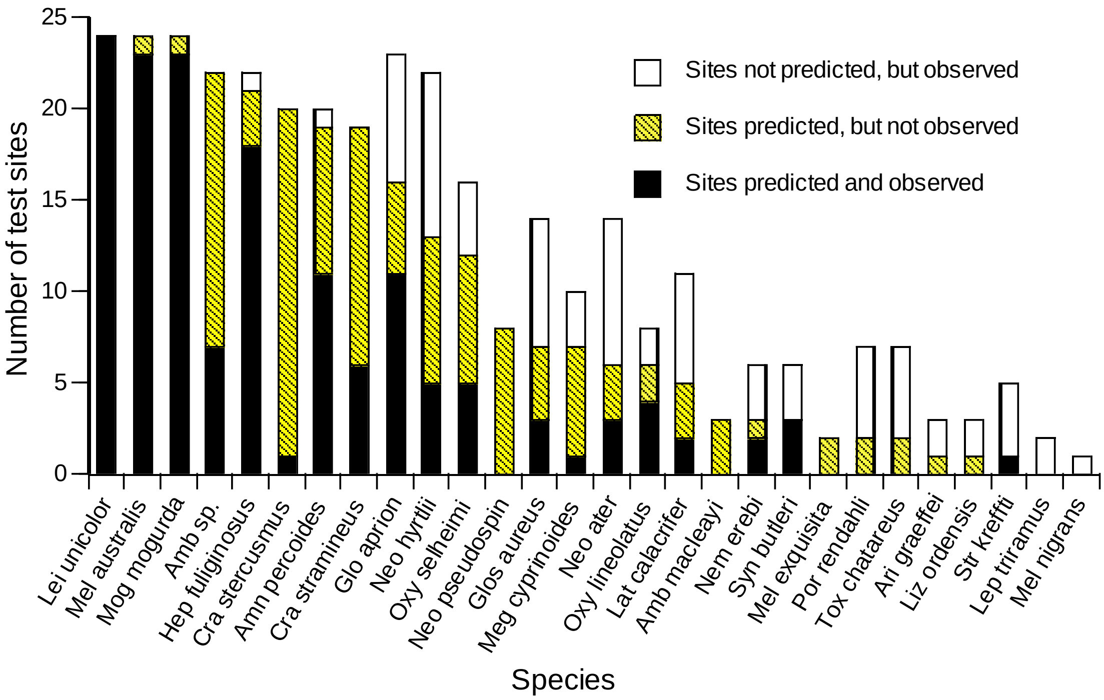
Attribute	Site type	Range	Mean ± S.D.
Predicted number of species (P)	Reference	3–23	12.76 ± 5.16
	Test	6–19	11.04 ± 3.61
Expected number of species (E) (sum of individual species probabilities of occurrence)	Reference	2.91–20.55	11.26 ± 4.62
	Test	4.57–16.12	9.50 ± 3.16
Observed number of species (O)	Reference	3–22	12.65 ± 5.09
	Test	4–17	9.79 ± 3.16
Observed/expected (O/E)	Reference	0.68–1.25	1.01 ± 0.13
	Test	0.47–1.09	0.68 ± 0.16

Relationships between fish assemblage indicators and anthropogenic disturbance

Fish assemblage composition at the test sites was often substantially different from that predicted by the model. O/E scores were often much lower than the range of values observed at reference sites, suggesting biological impairment at these test sites (Figure 3d; mean O/E = 0.68 ± 0.16, Table 3).

Examination of predictions of individual species and their pattern of occurrence revealed more detailed information about the potential responses of species to disturbance. For example, three species (*Lei unicolor, Mel australis and Mog mogurnda)* were predicted to occur at most sites and were actually observed, implying that these species may be relatively unaffected by disturbance (Figure 7). In contrast, several species that were also predicted to be widespread, actually occurred at fewer than half of sites predicted (Figure 7). These species included *Amb sp*., *Cra stercusmuscarum*, *Amn percoides* and *Cra stramineus*. Another set of species often occurred in sites in which they were not predicted; these species included *Glo aprion, Neo hyrtlii*, *Glo aureus* and *Neo ater*.

Figure 7: Summary of individual species predictions at test sites. The number of sites where each species was predicted to occur and actually observed, the number of sites where species were predicted to occur but were not actually observed, and the number of sites where species that were not predicted to occur but were actually observed are shown.



Discussion

Natural-functioning aquatic ecosystems deliver critical goods, services and long-term benefits to human welfare (Costanza et al. 1997; Baron et al. 2002). However, the impacts of human modifications to riverine landscapes have meant that, as aquatic ecosystems degrade, they become incapable of supplying goods and services to the same capacity as in the past (Rapport et al. 1998). Although aquatic ecosystems have numerous significant intrinsic values, the diminished ability of degraded ecosystems to sustain economic activity (Costanza et al. 1997) and human health has led to a greater recognition that their protection, remediation and restoration are critically important. Quantitative procedures are therefore required to assess aquatic ecosystem health and monitor biotic responses to remedial management.

Monitoring and assessment programs must be sufficiently well-designed and conducted to be able to deliver on their core intentions, i.e. to be able to determine whether natural systems are changing or have already changed in response to a human induced perturbation. In reality, this translates to the simultaneous minimisation of the frequency of Type I (incorrectly classifying a site as impaired) and Type II (incorrectly classifying a site as unimpaired) errors in the most cost-effective manner possible.

The strongly nested and hierarchical organisation of river landscapes suggests that aquatic ecosystems are strongly influenced by their surroundings at a variety of scales (Hunsaker and Levine 1995; Allan 2004). Consequently, human impacts on local assemblages are likely to be scale dependent, potentially being affected by processes operating at both landscape scales (e.g. agricultural runoff from upstream areas and barriers downstream) and local scales (e.g. riparian and instream habitat degradation)—a concept demonstrated in practice by many studies (e.g. Roth et al. 1996; Stauffer et al. 2000; Allan 2004; Kennard et al. 2006). That fish can integrate human disturbances arising from multiple sources at a range of spatial and temporal scales is seen as one of the benefits of using fish as indicators. However, the existence of multiple, scale-dependent mechanisms, potentially non-linear responses of biota to disturbance and the difficulties of separating current from historical effects can make it difficult to establish relationships between disturbance and ecosystem health indicators, or to diagnose the specific sources or mechanisms of human impact (Allan 2004).

This study demonstrated weak relationships of ecosystem health indicators based on native fish-assemblage composition, with a variety of sources of human disturbance potentially functioning at a range of spatial and temporal scales. These disturbances described impacts associated with catchment land use and associated local riparian, instream habitat and water quality degradation. The results of this study indicated that streams and rivers affected by human activity and modification are likely to display major differences in native fish-assemblage composition from that expected by comparison with similar areas not subject to human disturbance. These attributes of fish assemblages can therefore be used as summary indicators of degraded stream conditions, and these areas can be given appropriate attention for remediation. In this sense, these indictors may be amenable for inclusion in a broadscale ambient monitoring program to evaluate ecosystem health and identify areas that may require management intervention. However, their utility in diagnosing sources of disturbance or the mechanisms by which they influence fish is debatable and requires further examination.

Indicators based on deviations in native fish-assemblage composition from that expected revealed detailed information about the impacts of each source of disturbance on each native fish species, which, when coupled with knowledge of their life-history requirements, could potentially help to further elucidate the causes of disturbance to the aquatic ecosystem. However, post hoc correlative approaches and assumptions of linear relationships (such as in this study) have limitations in establishing cause and effect, no matter how explicit the conceptual basis for the linkages are. Ideally, experimental approaches are required, as is greater knowledge of the ecological requirements and environmental tolerances of the biota (Pusey et al. 2004). Human activities that may negatively affect individual native species do so via their influence on specific ecological traits (e.g. morphology, movement, trophic ecology, reproductive biology, environmental tolerances and habitat requirements). In this sense, the underlying metrics that describe the functional traits of assemblages and are incorporated into the index of biotic integrity potentially offer more diagnostic capabilities than interpretation of biotic patterns alone, as metrics such as those based on trophic and habitat requirements can provide a mechanistic basis for understanding cause and effect.

The use of ecological traits of fish communities to develop a quantitative mechanistic understanding of the functional linkages between environmental drivers and fish-species distributions or abundance patterns, is not well advanced in Australia (but see Olden and Kennard 2010), but is gaining increased attention in the US and Europe (e.g. Olden and Poff 2003, Vander Zanden et al. 2004). An important impediment in Australia has been the lack of quantitative ecological information for many species, and the disparate and inconsistent manner in which existing information has been collected and reported in the past (but see Pusey et al. (2004) for a systematic study of the ecological requirements native fishes). To incorporate such functional traits into a monitoring program in northern Australia will require a much greater understanding of how these attributes of biotic communities vary along natural environmental gradients (i.e. defining the reference condition). This knowledge deficit has reduced the capacity to quantitatively predict the consequences of future catchment management or flow-alteration scenarios on key elements of aquatic biodiversity such as fish (Bunn and Arthington 2002; Arthington and Pusey 2003). Nevertheless, habitat restoration (e.g. flow restoration, introduction of woody debris or riparian vegetation rehabilitation) may help prevent the establishment of alien fish populations, assist in the management of those already present (e.g. by reducing abundances) and benefit native fish populations (Arthington et al. 1990; Marchetti and Moyle 2001; Brown and Ford 2002).

The ultimate objective of a bio-assessment program should be to trigger some management intervention (e.g. mitigation, rehabilitation and/or restoration), otherwise it is a waste of limited resources simply to document declines in river health.

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Appendix 8: Results of fish surveys at 23 sites in the Daly River catchment

Table 13.8:Results of fish surveys at 23 sites in Daly River catchment.

Taxon	DG01	DG02	DP01	ED01	GA01	GA02	GA03	GA04	GA05	GT01	GT02	GT03	GT04
Ambassis sp.			1								1		1
Amniataba percoides	1	1	1	1					1				
Arius graeffei	1												
Craterocephalus stramineus	1	1	1		1	1	1	1	1		1	1	
Glossamia aprion		1	1	1	1		1	1	1	1		1	1
Glossogobius aureus	1			1				1	1				
Hephaestus bancrofti	1	1	1	1	1	1	1	1	1	1			
Lates calcarifer	1	1	1				1						
Leiopotherapon unicolor	1	1	1	1	1	1	1	1	1	1	1	1	1
Leptachirus triramus	1												
Liza ordensis	1												
Megalops cyprinoides			1						1	1			1
Melanotaenia nigrans			1										
Melanotaenia australis	1	1	1	1	1	1	1		1	1	1	1	1
Mogurnda mogurnda	1	1	1	1	1	1	1	1		1	1	1	1
Nematalosa erebi									1			1	
Neosilurus ater		1	1	1			1	1					1
Neosilurus hyrtlii				1	1	1				1	1	1	1
Oxyeleotris lineolatus								1	1				
Oxyeleotris selheimi		1	1					1					1
Strongylura kreffti		1	1						1				
Syncomistes butleri								1	1				
Toxotes chatareus	1								1				
Total number of species	12	11	14	9	7	6	8	10	13	7	6	7	9

Table 13.8 cont.: Results of fish surveys at 23 sites in Daly River catchment.

Taxon	HY01	HY02	MD01	SN01	SN02	SN03	SN04	SN05	ST01	ST02
Ambassis sp.	1		1					1	1	
Amniataba percoides	1	1	1					1	1	1
Arius graeffei	1									
Craterocephalus stramineus	1	1	1	1	1	1		1	1	1
Glossamia aprion	1	1	1	1	1	1			1	
Glossogobius aureus	1	1	1	1	1			1		
Hephaestus bancrofti	1	1	1	1	1			1	1	1
Lates calcarifer	1							1	1	1
Leiopotherapon unicolor	1	1	1	1	1	1	1	1	1	1
Leptachirus triramus	1									
Liza ordensis					1					
Megalops cyprinoides					1					
Melanotaenia nigrans										
Melanotaenia australis	1	1	1	1	1	1	1	1	1	1
Mogurnda mogurnda	1	1	1	1	1	1	1	1	1	1
Nematalosa erebi	1				1				1	
Neosilurus ater	1		1					1	1	
Neosilurus hyrtlii		1	1	1		1	1	1		
Oxyeleotris lineolatus	1		1					1	1	
Oxyeleotris selheimi		1	1	1	1					1
Strongylura kreffti	1				1					
Syncomistes butleri	1	1								
Toxotes chatareus					1				1	1
Total number of species	17	11	13	9	13	6	4	12	13	9

Appendix 9: Results of chironomid pupal exuviae at 23 sites in the Daly River catchment

Table 13.9: Results of survey of chironomid pupal exuviae at 23 sites in the Daly River catchment.

Taxon	DG01	DG02	DP01	ED01	GA01	GA02	GA03	GA04	GA05	GT01	GT02	GT03	GT04
?*Stictochironomus*													
Ablabesmyia				1				1					
Chironomus			1		1						1		
Cladopelma curtivalva													
Cladotanytarsus K2		1	1	1	1					1	1	1	1
Cladotanytarsus K3		1							1				
Cladotanytarsus K4			1	1	1							1	
Conochironomus cervus			1										
Corynoneura	1	1	1	1	1	1	1	1	1		1		1
Cricotopus albitarsis									1				
Cricotopus brevicornis	1			1	1	1	1	1	1			1	
Cryptochironomus griseidorsum			1							1			
Cryptotendipes		1		1									1
Dicrotendipes D1													
Dicrotendipes D3													
Dicrotendipes jobetus					1					1			
Dicrotendipes lindae		1											
Dicrotendipes nr tenuiforceps										1			
Djalmabatista		1											
Fittkauimyia													
Harnischia K1			1		1		1	1	1	1			1
Harnischia M1			1		1								
Larsia		1	1	1									
Nanocladius	1	1		1		1		1	1				
Nilotanypus		1				1							
Parachironomus				1						1	1		
Parakiefferiella K2	1			1	1	1	1	1	1	1	1		1
Paramerina		1	1	1		1				1	1		
Parametriocnemus					1		1						

Taxon	DG01	DG02	DP01	ED01	GA01	GA02	GA03	GA04	GA05	GT01	GT02	GT03	GT04
Paratanytarsus D1			1					1		1	1		1
Paratanytarsus grimmi													1
Paratanytarsus K1	1	1	1					1	1	1			
Paratendipes K1			1	1	1		1			1		1	
Paratendipes K2		1	1		1			1		1			1
Polypedilum D1						1							
Polypedilum D2			1		1					1			
Polypedilum D3				1									
Polypedilum D4													
Polypedilum D5		1											
Polypedilum K5		1	1	1									
Polypedilum leei			1										
Procladius		1	1		1				1	1			
Rheocricotopus	1	1	1	1	1	1	1	1	1	1	1	1	1
Rheotanytarsus christinae			1	1	1	1		1			1	1	1
Rheotanytarsus johnstoni		1		1		1				1			
Rheotanytarsus oss		1											
Robackia	1						1						
Skusella				1									
Stempellina		1		1									
Stempellinella	1	1		1		1	1	1	1	1	1		1
Stenochironomus		1	1							1			
Tanypus													
Tanytarsus D1													
Tanytarsus dostinei		1				1							
Tanytarsus dycei		1		1						1			
Tanytarsus edwardi		1								1			
Tanytarsus K10				1									
Tanytarsus K14				1									
Tanytarsus manleyensis					1		1	1			1		1
Tanytarsus micksmithi		1		1									
Tanytarsus 'patch'			1							1			
Tanytarsus reidi								1	1				
Tanytarsus richardsi		1	1					1		1			1

Taxon	DG01	DG02	DP01	ED01	GA01	GA02	GA03	GA04	GA05	GT01	GT02	GT03	GT04
Tanytarsus rosario		1											
Tanytarsus 'tubercles'	1				1						1		
Thienemaniella K1		1		1		1	1	1	1				
Thienemaniella K2	1			1		1	1						
Thienemannimyia													
Unk 'forked tubercles'													
Unk Gen D4													
Unk Gen D5				1									
Xenochironomus D1													
Total number of species	10	28	23	27	18	14	12	16	13	22	12	6	13

Table 13.9 cont.: Results of survey of chironomid pupal exuviae at 23 sites in the Daly River catchment.

Taxon	HY01	HY02	MD01	SN01	SN02	SN03	SN04	SN05	ST01	ST02
?*Stictochironomus*								1		
Ablabesmyia		1								
Chironomus					1	1		1		
Cladopelma curtivalva		1	1							
Cladotanytarsus K2	1		1	1		1	1			
Cladotanytarsus K3		1			1			1		
Cladotanytarsus K4			1		1			1		1
Conochironomus cervus										
Corynoneura		1		1	1		1	1		1
Cricotopus albitarsis										
Cricotopus brevicornis		1	1		1			1	1	1
Cryptochironomus griseidorsum					1					
Cryptotendipes				1			1	1	1	1
Dicrotendipes D1		1								
Dicrotendipes D3					1			1		
Dicrotendipes jobetus						1				
Dicrotendipes lindae										
Dicrotendipes nr tenuiforceps		1	1		1					
Djalmabatista										
Fittkauimyia			1							
Harnischia K1				1	1			1		
Harnischia M1							1	1		
Larsia		1	1						1	
Nanocladius		1	1					1	1	1
Nilotanypus				1				1		1
Parachironomus										
Parakiefferiella K2	1	1	1	1	1		1	1	1	1
Paramerina	1	1	1				1	1		
Parametriocnemus										
Paratanytarsus D1		1				1		1		
Paratanytarsus grimmi							1			
Paratanytarsus K1	1	1						1	1	
Paratendipes K1			1		1		1		1	1
Paratendipes K2	1	1			1					
Polypedilum D1				1						
Polypedilum D2	1							1		
Polypedilum D3	1		1							
Polypedilum D4								1		
Polypedilum D5										
Polypedilum K5					1			1		
Polypedilum leei										
Procladius	1	1	1			1	1	1		
Rheocricotopus		1	1						1	1
Rheotanytarsus christinae		1	1	1				1		
Rheotanytarsus johnstoni			1				1			
Rheotanytarsus oss										
Robackia										1
Skusella	1							1		
Stempellina										
Stempellinella	1	1	1	1	1			1	1	1
Stenochironomus			1		1			1		

Tanypus						1				
Tanytarsus D1								1		
Tanytarsus dostinei										1
Tanytarsus dycei		1				1				
Tanytarsus edwardi	1	1								
Tanytarsus K10										
Tanytarsus K14										
Tanytarsus manleyensis	1	1	1			1	1		1	1
Tanytarsus micksmithi		1								
Tanytarsus 'patch'	1	1	1							
Tanytarsus reidi		1		1					1	
Tanytarsus richardsi	1	1	1		1			1	1	
Tanytarsus rosario										
Tanytarsus 'tubercles'										
Thienemaniella K1		1								1
Thienemaniella K2		1								
Thienemannimyia		1								1
Unk 'forked tubercles'					1					
Unk Gen D4								1		
Unk Gen D5										
Xenochironomus D1		1								
Total number of species	14	29	21	10	17	8	11	27	12	15

Appendix 10: Results of macroinvertebrate communities at 23 sites in the Daly River catchment

Table 13.10: Results of surveys of macroinvertebrate communities of edge habitats at 23 sites in Daly River catchment.

Taxon	DG01	DG02	DP01	ED01	GA01	GA02	GA03	GA04	GA05	GT01	GT02	GT03	GT04
?*Stictochironomus*													
Ablabesmyia		1			1					1			
Albia		1											
Amphiops						1						1	
Anisocentropus		2											
Anisoptera	26	8	3	2	4	17	17	7	7	5			1
Atalophlebia				5									
Australiobates													
Austrogomphus						1							
Austrolimnius	27	13	10	24		2		43	5		1		1
Berosus							1						
Caridina	6	7	11	2	9	5	6				2	1	
Ceratopogoninae	6	13	2	13	6	9	15		16	2	22	13	24
Cherax													
Cheumatopsyche		1					8	1					
Chimarra		4											
Chironomus					2						2		2
Cladotanytarsus							1		2		1	6	8
Clinotanypus					1								
Cloeon		1	1	7	4					10	18	3	14
Clypeodytes				22				1			1		
Coaustraliobates				1									
Collembola													
Conochironomus				1									
Corbiculina									6				
Corixidae		2	8		67	6				58	1	1	2
Coxelmis													

Cricotopus	3					1	1	29	4			7	
Cryptochironomus									1				
Cryptotendipes													1
Culicidae			2	1	8					14	17	1	
Dicrotendipes	1	19	6		1				8			2	12
Diplonychus													
Djalmabatista													
Ecnomina	3	1			1					3			
Ecnomus	3	3	1	1	3		8		3		1	8	8
Empididae						1	3	6	3			2	
Enochrus		1						1			1	1	
Ferrissia												3	
Fittkauimyia													
Forcipomyiinae					1	2					3	3	1
Frontipoda spinosa			1	5									
Gelastocoridae													
Georissus						1							
Gerridae							1				2	1	1
Graphelmis		1	2	1		1				3	1		
Harnischia					1				3	2			7
Hebridae											1		
Hellyethira		13	3	1		2			2	2			
Hydraena				6		2	1				4	4	1
Hydrochus		1	4	20	4	5	3	1	2	4	8	20	5
Hydrodroma										1		70	
Hydroglyphus				10			1						
Hydrometridae											1		
Hydroptila								3	17				
Hydrovatus		9					1			1			
Kiefferulus					1						1		1
Koenikea						1				17		4	2
Laccophilus		2	1	3	4	1					1		
Larsia													
Leptocerus													
Limbodessus											1		1

Limnesia												1	
Limnichidae					2		2			1	1	4	1
Macrobrachium	4			1	1	4	13		2	6	6	1	5
Macrogyrus									1				
Mesoveliidae				1	1	1	1		1		3	2	2
Microchironomus													
Microtendipes						23			2			4	26
Monatractides									1				
Nematoda					1								1
Neohydrocoptus		2											
Neolimnochares													
Neumania													
Nilotanypus									1				1
Notomicrus				1		1	1				3		
Notonectidae			1		33					6	1		
Ochthebius											1		
Oecetis	13	11	2	10	5	6			7	1	2		
Oligochaeta	4	1	1				1	1		1	2	4	1
Oribatida							1	1					
Orthotrichia		1		1		2	1	11	1				
Oxus													
Parachironomus		8		1									
Paracymus		1		4				2			4	2	
Parakiefferiella	19		1		1		1	6	6		3		12
Paramerina				4		1					3		2
Paranyctiophylax													
Paraplea	1	4	2	1	8	4	1		1		2	1	1
Paratanytarsus		1			1	1	1	6	1	9	2		4
Paratendipes							1					2	
Plectrocnemia													
Polypedilum	1	1		4	2	3	2		2				8
Potamophilinus	1					1	1						
Procladius													
Psalitrus													
Pseudocloeon	7			1		3	15	31	47				

Pseudohydryphantes													
Psychodidae					1						1		
Pyralidae	5	1		1	1	1		3	1				
Recifella			1							2			3
Rheocricotopus	1					2	2	1	1				
Rheotanytarsus		4				13	10	15		1	2	2	1
Riethia		4		1						4			
Simuliidae							5						
Sisyriidae													
Sphaerius													
Staphylinidae													
Stempellina													
Stempellinella		2		1			1		14			1	
Stenochironomus				3			1			5	2		
Stratiomyidae					1		1			1	2	3	1
Tabanidae													
Tanytarsus	1	13	7	4	1	8	2	16	18	1	9	5	21
Tasmanocoenis	36	12	55	10	8	56	24	19	35	20	69	11	15
Thiara	4												
Thienemannimyia	1	2						1	1				
Thraulus					2		1				2		3
Tipulidae				1	1								
Triaenodes	30	69	35	38	17	15	38	2	4	11	8	6	1
Tricholeiochiton													
Triplectides	1	1	5	2	2		1		1	2	1		
Trombidioidea											1		
Unid scirtid larva													
Unionicola				6						6		3	4
Unk genus ?Cranston													2
Unknown Genus D1			1										1
Unknown Genus K1		1											
Veliidae				2		1	2				5	1	1
Wundacaenis	7	4	48		11	15		3	1	12		23	
Xenochironomus		1											
Zavreliella												1	

Zygoptera		5	4	6	5	5	3			3	3	2	4
Total number of taxa	25	42	27	41	38	38	41	24	36	32	46	39	42

Figure 13.10 cont.: Results of surveys of macroinvertebrate communities of edge habitats at 23 sites in Daly River catchment.

Taxon	HY01	HY02	MD01	SN01	SN02	SN03	SN04	SN05	ST01	ST02
?*Stictochironomus*		2			3					
Ablabesmyia	3						1			
Albia		1								
Amphiops	1									
Anisocentropus		1								
Anisoptera	1	3	2	3	1		5		22	14
Atalophlebia										
Australiobates		2								
Austrogomphus										
Austrolimnius	1	3	2		6			3	8	5
Berosus						1				
Caridina	13	2			7			17	1	3
Ceratopogoninae	8	11		55	10	5	3	1	7	24
Cherax						1				
Cheumatopsyche									8	
Chimarra										
Chironomus		1				2				
Cladotanytarsus	1		5	2		1				
Clinotanypus	1				1			1		
Cloeon	4	15	11	16	9	5	15	21		
Clypeodytes	2	1			1	1				
Coaustraliobates										
Collembola				1						
Conochironomus										
Corbiculina	4									
Corixidae	7	6		1	19	32	2	113		
Coxelmis					4					
Cricotopus				6					2	7
Cryptochironomus				1						1
Cryptotendipes										

Culicidae	4	7	2		1	53		2		
Dicrotendipes	4		1	5			5		1	
Diplonychus		1								
Djalmabatista										2
Ecnomina	10		4		3	1			1	1
Ecnomus	1		3				1		2	11
Empididae										1
Enochrus										1
Ferrissia					1					
Fittkauimyia	1				2			1		
Forcipomyiinae	1						1			
Frontipoda spinosa	3		3		1					
Gelastocoridae	1									
Georissus										
Gerridae			1	1						
Graphelmis	1									
Harnischia				1	2					2
Hebridae										
Hellyethira	3	19	6	3						3
Hydraena	4	1	2	1	4	3			2	1
Hydrochus	3		3	1	8	6	2		8	2
Hydrodroma	2		18						2	6
Hydroglyphus	1				13	1		1	2	1
Hydrometridae										
Hydroptila										
Hydrovatus	2		1	5	7				15	3
Kiefferulus					2	4		1	1	
Koenikea		1			3		10			
Laccophilus	1				7	1		1		
Larsia	2	14	2	8						3
Leptocerus					1					
Limbodessus						2				
Limnesia	1		3		1					1
Limnichidae	1				1					
Macrobrachium	1		1	2		5	19	4	7	8

Macrogyrus										
Mesoveliidae	1		2		2				1	1
Microchironomus		2								
Microtendipes				4	11			2	1	4
Monatractides									3	2
Nematoda				1						
Neohydrocoptus	1	1			2				11	
Neolimnochares	3									
Neumania							1			
Nilotanypus										
Notomicrus	1				2				1	
Notonectidae					14	7	1			
Ochthebius										
Oecetis	1	1	3				2	4	13	13
Oligochaeta			1	2	1		1	2		
Oribatida	1	2							1	
Orthotrichia	1	10	5					2	1	5
Oxus		1								
Parachironomus				1		2				
Paracymus		2			1					1
Parakiefferiella			1	28			1	1		1
Paramerina	2	2	1		3	4	2			2
Paranyctiophylax					1					
Paraplea	10	1	4		27	17		5	4	
Paratanytarsus	1	1	3			1		2	1	5
Paratendipes				12					1	1
Plectrocnemia					1					
Polypedilum	2	4	4	5	2	1				1
Potamophilinus						1				
Procladius		3		3						
Psalitrus	2									
Pseudocloeon									21	34
Pseudohydryphantes	1									
Psychodidae				1						1
Pyralidae										3

Recifella										
Rheocricotopus										
Rheotanytarsus			2			2	1	1	2	6
Riethia										
Simuliidae									1	
Sisyriidae						1				
Sphaerius				4						
Staphylinidae		1								
Stempellina										7
Stempellinella		2	5	1						
Stenochironomus	4			2	2			4		1
Stratiomyidae	2		2		3	5				
Tabanidae			1							
Tanytarsus	3	27	23	19		5	1	1	3	20
Tasmanocoenis	6	34	20	11	8	24	87	8	4	5
Thiara	17			2	3					
Thienemannimyia									3	4
Thraulus	1									
Tipulidae	1			1						
Triaenodes	73	12	48		2	12	12	8	44	20
Tricholeiochiton		2								
Triplectides	4	1	2		8	2	2			1
Trombidioidea										
Unid scirtid larva					1					
Unionicola		2	3			5				
Unk genus ?Cranston										
Unknown Genus D1		1		1						
Unknown Genus K1	2				1					
Veliidae		4			5					
Wundacaenis	5	17	7	7		17	45	1	6	4
Xenochironomus										
Zavreliella		1			1					
Zygoptera	5	2	10	2	5	7	12	7		4
Total number of taxa	57	43	38	36	49	34	24	26	35	45

Appendix 11: Environmental variables for 23 sites in the Daly River catchment

Table 13.11: Environmental variables for 23 sites in Daly River catchment, used in testing sensitivity of indicators to disturbance.

Site #	Site	Str_ord	Dist_src	Catch	Clear	Bank	LUMP	pH	EC (µS/cm)	Turbidity (NTU)	Tot N (mg/L)	Tot P (mg/L)
1	DG01	4	67.4	1175.5	8.5	1	0.67	7.36	219.0	3.08	0.1200	0.0030
2	DG02	4	46.6	523.6	1.9	55	0.65	7.02	17.0	5.24	0.0790	0.0090
3	DP01	3	28.5	141.9	2.2	84	0.65	7.92	540.0	3.76	0.1370	0.0060
4	ED01	4	36.7	443.1	1.2	3	1.00	7.49	16.0	2.73	0.0560	0.0020
5	GA01	3	15.1	47.1	37.6	31	0.64	7.00	460.4	3.18	0.1820	0.0097
6	GA02	3	20.8	92.6	52.0	44	0.63	7.97	473.0	2.33	0.0430	0.0060
7	GA03	3	27.0	139.0	38.4	53	0.64	8.00	615.2	3.42	0.1476	0.0068
8	GA04	3	48.7	419.8	49.9	10	0.59	8.00	547.6	2.17	0.1054	0.0180
9	GA05	4	52.5	861.1	58.6	19	0.56	8.05	555.0	2.49	0.1620	0.0168
10	GT01	1	6.7	14.8	2.1	12	0.65	7.26	195.0	7.91	0.1390	0.0180
11	GT02	2	15.6	44.1	30.2	60	0.65	7.43	589.0	4.51	0.1410	0.0070
12	GT03	1	5.0	17.8	44.8	75	0.60	8.01	620.0	2.89	0.2055	0.0065
13	GT04	2	8.0	24.3	88.9	63	0.50	7.75	620.0	5.4	1.9050	0.0140
14	HY01	4	46.7	523.2	15.6	4	0.65	7.93	570.0	2.61	0.0510	0.0030
15	HY02	4	42.6	382.5	24.8	15	0.65	7.91	606.00	1.88	0.0610	0.0045
16	MD01	3	35.8	302.7	5.3	1	0.69	7.88	614.00	3.18	0.0870	0.0070
17	SN01	1	6.6	49.8	50.3	94	0.62	8.22	502.00	4.82	0.0875	0.0038
18	SN02	2	14.8	96.0	56.8	20	0.61	7.93	585.00	2.13	0.0860	0.0023
19	SN03	2	9.4	34.8	84.2	119	0.50	8.00	541.00	44.07	0.8395	0.0320
20	SN04	1	1.4	1.8	100.0	119	0.47	7.46	484.00	5.06	0.3740	0.0050
21	SN05	4	27.8	349.2	74.9	21	0.54	8.02	573.00	4.58	0.1318	0.0073
22	ST01	4	67.8	1013.7	18.3	1	0.69	8.26	556.00	1.69	0.0827	0.0033
23	ST02	4	58.1	892.3	13.8	69	0.68	8.10	599.00	5.81	0.0470	0.0020

Appendix 12: Results of generalised linear modelling of dependent variables.

Table 13.12 a): Results of generalised linear modelling of dependent variable fish O/E (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
Null	13.62	2	-22.65	0.00	0.43	0.00
PC1	14.78	3	-22.30	0.35	0.36	9.57
PC2	13.63	3	-19.99	2.65	0.11	0.04
PC1 + PC2	14.79	4	-19.35	3.30	0.08	9.61
PC1*PC2	15.17	5	-16.80	5.85	0.02	12.55

Table 13.12b): Results of generalised linear modelling of dependent variable fish species richness (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
PC1 + PC2	-51.22	4	112.66	0.00	0.71	49.53
PC1*PC2	-51.00	5	115.53	2.87	0.17	50.47
PC1	-54.66	3	116.58	3.93	0.10	31.91
PC2	-56.85	3	120.97	8.31	0.01	17.62
Null	-59.08	2	122.76	10.11	0.00	0.00

Table 13.12c): Results of generalised linear modelling of dependent variable macroinvertebrate O/E (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
PC1	13.51	3	-19.76	0.00	0.47	19.85
PC1 + PC2	14.36	4	-18.50	1.27	0.25	25.53
Null	10.97	2	-17.34	2.43	0.14	0.00
PC2	11.64	3	-16.02	3.74	0.07	5.68
PC1*PC2	14.58	5	-15.63	4.13	0.06	26.95

Table 13.12d): Results of generalised linear modelling of dependent variable chironomid pupal richness (glm family Gaussian, log link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
PC1 + PC2	-72.17	4	154.56	0.00	0.36	28.55
PC1	-73.85	3	154.96	0.40	0.30	17.31
PC2	-74.70	3	156.66	2.10	0.13	10.99
Null	-76.04	2	156.67	2.11	0.13	0.00
PC1*PC2	-71.88	5	157.30	2.74	0.09	30.30

Appendix 13: Results of generalised linear modelling of predictor variables.

Table 13.13a: Results of generalised linear modelling of dependent variable fish model 0/E (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
RDI	15.83	3	-24.39	0.00	0.30	17.45
Clear	15.35	3	-23.43	0.96	0.19	13.92
Catch + RDI	16.56	4	-22.90	1.50	0.14	22.53
Null	13.62	2	-22.65	1.75	0.13	0.00
Bank	14.38	3	-21.50	2.90	0.07	6.36
Catch + clear	15.79	4	-21.36	3.04	0.07	17.16
Catch	13.63	3	-19.99	4.41	0.03	0.01
Catch*RDI	16.72	5	-19.91	4.49	0.03	23.60
Catch + bank	14.70	4	-19.18	5.21	0.02	8.95
Catch*clear	15.88	5	-18.23	6.16	0.01	17.81
Clear + RDI + catch + bank	17.12	6	-16.99	7.40	0.01	26.22
Catch*bank	14.70	5	-15.88	8.52	0.00	8.96

Table 13.13b: Results of generalised linear modelling of dependent variable fish richness (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
Catch + bank	-53.02	4	116.27	0.00	0.27	40.95
Bank	-54.61	3	116.48	0.21	0.25	32.23
Catch	-55.08	3	117.43	1.16	0.15	29.36
Catch + clear	-54.40	4	119.03	2.76	0.07	33.42
Catch*RDI	-52.99	5	119.51	3.25	0.05	41.11
Catch*bank	-53.02	5	119.57	3.30	0.05	40.96
Catch + RDI	-54.72	4	119.67	3.40	0.05	31.55
Catch*clear	-53.16	5	119.85	3.59	0.05	40.23
Clear	-57.01	3	121.28	5.02	0.02	16.48
RDI	-57.31	3	121.88	5.61	0.02	14.28
Null	-59.08	2	122.76	6.49	0.01	0.00
Clear + RDI + catch + bank	-52.87	6	123.00	6.73	0.01	41.71

Table 13.13c: Results of generalised linear modelling of dependent variable macroinvertebrate O/E (glm family Gaussian, identity link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
Catch	16.77	3	-26.28	0.00	0.28	26.78
Catch + RDI	17.98	4	-25.74	0.54	0.21	34.09
RDI	16.14	3	-25.02	1.26	0.15	22.66
Catch + clear	17.28	4	-24.34	1.94	0.11	29.95
Catch + bank	16.77	4	-23.33	2.96	0.06	26.79
Catch*RDI	18.20	5	-22.86	3.42	0.05	35.31
Clear	14.93	3	-22.59	3.70	0.04	14.02
Null	13.19	2	-21.78	4.51	0.03	0.00
Catch*clear	17.31	5	-21.10	5.19	0.02	30.14
Bank	13.95	3	-20.63	5.65	0.02	6.38
Catch*bank	17.07	5	-20.62	5.67	0.02	28.67
Clear + RDI + catch + bank	18.39	6	-19.53	6.76	0.01	36.38

Table 13.14d): Results of generalised linear modelling of dependent variable chironomid pupal richness (glm family Gaussian, log link).

Model type	Log likelihood	k	AICc	d.AICc	wi	pcdev
RDI	-73.17	3	153.59	0.00	0.20	22.09
Clear	-73.44	3	154.14	0.55	0.15	20.21
Catch*bank	-70.41	5	154.35	0.76	0.14	38.67
Catch + RDI	-72.13	4	154.48	0.89	0.13	28.80
Catch*RDI	-70.66	5	154.84	1.25	0.11	37.36
Bank	-74.08	3	155.41	1.82	0.08	15.67
Catch + clear	-72.92	4	156.05	2.46	0.06	23.76
Null	-76.04	2	156.67	3.08	0.04	0.00
Catch + bank	-73.24	4	156.70	3.10	0.04	21.60
Catch*Clear	-72.16	5	157.84	4.25	0.02	28.63
Clear + RDI + catch + bank	-70.73	6	158.71	5.12	0.02	36.96
Catch	-76.02	3	159.31	5.71	0.01	0.12